



# Modeling and multi-criteria decision support for thermal comfort in urban areas

Aiman Mazhar Qureshi

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## Thèse de Doctorat

*Mention : Science pour l'Ingénieur  
Spécialité : Automatique*

*Présentée à l'Ecole Doctorale en Sciences Technologie et Santé (ED 585)*

**De l'Université de Picardie Jules Verne**

Par

**Aiman Mazhar Qureshi**

Pour obtenir le grade de Docteur de l'Université de Picardie Jules Verne

***Modélisation et aide à la décision multicritère du  
confort thermique en milieu urbain***

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# Declaration of Authorship

I, **Aiman Mazhar Qureshi**, declare that this thesis titled, “Modeling and multi-criteria decision making of thermal comfort in urban areas” and the work presented in it are my own. I confirm that:

- ❖ This work was done wholly or mainly while in candidature for a research degree at this University.
- ❖ Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- ❖ Where I have consulted the published work of others, this is always clearly attributed.
- ❖ Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- ❖ I have acknowledged all main sources of help.

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

**Signed:**

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**Date:**

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*" Failure is not fatal until we surrender,  
trying again is the key to glorious victory."*

**Allama Muhammad Iqbal**



# Abstract

Urban areas are the prevalent places of residence for people and are vulnerable to exasperating weather conditions such as heat stress. Periods of heat waves are increasingly reoccurring in the current atmosphere, and they are known to pose a serious and major threat to the health of human beings all over the world. Urban heat islands and heat waves increase thermal risks in urban areas and the vulnerability of the urban population.

The increase in the number of heat episodes in urban areas has become a significant concern due to its adverse effects on human health and economic activities. The objective of this work is to identify the sensitivity of thermal comfort and their action variables, the modeling of thermal stress using the most influential meteorological variables, the identification of risk factors and highlight the correlation of meteorological trends and influencing parameters, solutions for mitigating heat stress and mathematical support for decision-making.

Several machine and deep learning techniques were used for the system dynamic modeling of the thermal comfort. Optimized results are obtained from the Gated Recurrent Unit (GRU) model which is used for the development of a web simulation tool allowing the inhabitants to evaluate their level of comfort according to the weather conditions.

A heat vulnerability index map has been developed to indicate the vulnerability of occupants considering different aspects in a medium-sized city such as planning, green space, density, energy, air quality, water bodies and extreme heat events. The obtained results highlighted that poor air quality and heat events are interrelated, which draws the attention for decision-makers to intervene the additional measures in high-risk places. Field monitoring was carried out using sensors and a thermal camera to measure relevant variables and take action to minimize the effects of heat stress. In Last, multi-criteria decision-making methods were applied for the initial development of a decision support tool for selection of urban heat resilience interventions that allows flexible, dynamic, and predictive use for designers and the users.

**Keywords:** Urban heat stress; Sensitivity; Modeling; Mitigation; Vulnerability; Decision-making.

## Résumé

Les zones urbaines sont les principaux lieux de résidence des personnes et sont vulnérables aux conditions météorologiques exaspérantes telle que le stress thermique. Les périodes de vagues de chaleur se reproduisent de plus en plus dans l'atmosphère, et elles sont connues pour constituer une menace sérieuse et majeure pour la santé des êtres humains partout dans le monde. Les îlots de chaleur urbains et les canicules augmentent les risques thermiques en zone urbaine et la vulnérabilité de sa population.

L'augmentation du nombre de vagues de chaleur dans les zones urbaines est devenue une préoccupation importante en raison de ses effets néfastes sur la santé humaine et les activités économiques. L'objectif de ce travail est d'identifier la sensibilité du confort thermique et de leurs variables d'action, la modélisation des contraintes thermiques à l'aide des variables météorologiques les plus influentes, l'identification des facteurs de risque et de mettre en évidence la corrélation des tendances météorologiques et des paramètres influents, les solutions d'atténuation du stress thermique et l'aide à la prise de décision.

Plusieurs techniques d'apprentissage automatique ont été utilisées pour la modélisation dynamique du confort thermique. Des résultats optimisés sont obtenus à partir du modèle Gated Recurrent Unit (GRU) qui est utilisé pour le développement d'un outil de simulation web permettant aux habitants d'évaluer leur niveau de confort en fonction des conditions météorologiques.

Une carte d'indice de vulnérabilité à la chaleur a été développée pour indiquer la vulnérabilité des occupants en tenant compte de différents aspects dans une ville de taille moyenne tels que la planification, les espaces verts, la densité, l'énergie, la qualité de l'air, les plans d'eau et les épisodes de chaleur extrême. Les résultats obtenus ont mis en évidence que la mauvaise qualité de l'air et les épisodes de chaleur sont interdépendants, ce qui attire l'attention des décideurs à prendre des mesures supplémentaires dans les lieux à haut risque. La surveillance sur le terrain est effectuée à l'aide de capteurs et d'une caméra thermique pour mesurer les variables pertinentes et prendre des mesures pour minimiser les effets du stress thermique. Finalement, des méthodes d'aide à la décision multicritères ont

été appliquées pour le développement initial d'un outil d'aide à la décision pour la sélection d'interventions de résilience thermique urbaine qui permet une utilisation flexible, dynamique et prédictive pour les concepteurs et les utilisateurs.

**Mots-clés :** Stress thermique urbain ; Sensibilité ; La modélisation ; Atténuation ; Vulnérabilité ; La prise de décision

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# **General Introduction**

Heat stress is an uncomfortable feeling, when the body is unable to sustain a healthy temperature in response to the hot environmental condition during daily activities such as sleeping, travel, work. The growing intensity of heat stress in urban areas has become a significant concern due to its direct and adverse effect on human health and economic activities. [1], [2].

It has been observed in the past recent decades that the rapid increase in the intensity of heatwaves in urban settings has been following global warming. These extreme heatwaves pose a hazardous impact on the urban environment and the population, ultimately increasing the rate of morbidity and mortality.

Reduced natural landscapes in urban areas due to population density is one of the major factors which increases the vulnerability of heat waves and giving rise to the phenomenon of "Urban Heat Island" (UHI) - where the city is hotter than the surrounding. The density of urban areas is rapidly increasing due to the increased birth rates and migration of people from rural settings to improve their lives by means of better income, resources and a better society [3].

The everyday human anthropogenic activities in urban communities emanate an enormous number of contamination particles into the urban air which increases exposure of people to air toxins. Moreover, the superposition of heat stress and air contamination makes people progressively helpless with the impact of each appropriate risk [4].

Many cities applied heat emergency response plans to reduce the mortality rates during the heatwave. The combination of high heat waves and poor air quality leads to the health risks. Heat stress can lead to heat exhaustion, heat cramps, and rashes and due to long term exposure, it causes heat stroke. Children, aged people, people live alone, pregnant women, asthma and cardio patients are particularly vulnerable to both extreme events (heat and polluted) which requires additional interventions.



In this present situation, if nothing is adapted to alleviate the intensity of heat stress in urban areas, the temperature extremity would spread greatly across the earth's sphere by 2100 [5]. The unchecked elevation in the extreme heat would impact highly on the communities and ecosystems, ultimately making it harder to cope with it [6].

Heat-stress mitigation strategies are needs to be applied in urban areas, in order to sustain the environment and human health [7]. Intervening heat resilience measures, developing a decision support system is a challenge. This thesis deals with the thermal comfort which combines the heat stress prediction modeling, heat vulnerability mapping, field measurements and application of multi-criteria decision methods. This thesis is composed of 5 chapters. Chapter 1-5 are based on journal articles; the conclusions are provided at the end. The thesis outlines are given below.

**Chapter 1:** Reviews a total of 71 journal papers, published in English and focused on the interventions which improves thermal comfort. Cooling effect data are extracted from these journal papers to investigate the efficacy of heat stress mitigation strategies. Based on the analysis of the extracted data, past achievements on this research topic are documented, and average cooling of installation of green blue and grey interventions are estimated

Moreover, a review study on Decision Support Tools (DSTs) is conducted. The existing published studies on multicriteria decision making, toolkits and simulation tools in the field of heat stress and urban heat island are reviewed. The tools are compared on benchmarking criteria which must covered by decision support system in improvement thermal comfort in urban areas. Past achievements on this research topic are presented, various knowledge gaps are identified and recommendations for better version of any DST are discussed.

**Chapter 2:** This chapter is a state of art which includes the background of heat stress and existing models are discussed in these sections. A survey on outdoor heat stress indices is conducted to present their existing mathematical models and highlight the different heat indices are being used officially for measuring thermal comfort in different regions across the globe. After the survey of heat indices, it is noticed that most indices can be measured and calibrated directly by using equations and some secondary

indices can be estimated by different complexed methods evaluated by their models. The sensitivity analysis of most common heat stress indices which can be estimated by direct mathematical models i.e., CET, HI, SSI, PMV, DI, WBGT, UTCI are carried out and calculated the variation coefficient for each variable by partial differential equation. These operational indices are also simulated analyse sensitivity of discomfort zones by certain variations in summer under minmax function.

**Chapter 3:** Physiological Equivalent Temperature (PET) and Predicted Mean Vote (PMV) are complexed heat indices which can be calculated by Munich Energy balance models for Individuals and Fangers models respectively. System dynamic and artificial intelligence is used for predictive modeling of PET, Mean Radiant Temperature and PMV. The five most important meteorological parameters such as air temperature, global radiation, relative humidity, surface temperature and wind speed are considered for Heat stress assessment. Three machine learning approaches, namely Support vector machine, Decision tree and Random Forest, are used to predict the heat stress. Afterwards, Deep learning approaches such as Long short-term memory, Gated Recurrent Unit (GRU) and Simple recurrent neural networks are used to evaluate the performance of the developed approaches. It is observed among others GRU is a promising technology, the results with higher accuracy are obtained from this algorithm. Web based simulation tool is developed for the users for heat stress assessment which allows users to select the range of thermal comfort scales based on their perception that depends on the age factor, local weather adaptability, and habit of tolerating the heat events. It also gives a warning to the user by colour code about the level of discomfort which helps them to schedule and manage their outdoor activities.

**Chapter 4:** After the heat stress assessment, it is also required to analyse the hotspots and vulnerable areas. We evaluated the Heat Vulnerability Index (HVI) in Amiens for extreme heat days recorded for three years (2018–2020). We used the principal component analysis (PCA) technique for fine-scale vulnerability mapping. The main types of considered data included (a) socioeconomic and demographic data, (b) air pollution, (c) land use and cover, (d) elderly heat illness, (e) social vulnerability, and (f) remote sensing data (land surface temperature (LST), mean elevation, normalized difference vegetation index (NDVI), and normalized difference water index (NDWI)). The output maps identified the hot zones through comprehensive GIS analysis. The resultant maps showed that high HVI

exists in three typical areas: (1) areas with dense population and low vegetation, (2) areas with artificial surfaces (built-up areas), and (3) industrial zones. Low-HVI areas are in natural landscapes such as rivers and grasslands. This approach can be helpful for decision makers to target hot areas for planning heat resilience measures. In addition, cooling effect of three plant species which are mainly exist at public spaces in city centre are measured during last summers (2021) in Amiens using sensor named Kestrel 5400.

**Chapter 5:** Selection of intervention for desirable locations is important for decision makers considering certain criteria. In this chapter, Multi-Criteria Decision Methods (MCDM) are applied which helps to select and prioritize mitigation measures step by step. Firstly, An Analytic Hierarchy Process (AHP) based approach is applied in choosing appropriate measures for hotspots. The evaluation of the measures is obtained from a questionnaire where human judgment is used for a comparison, based on their perception and priorities. The limitations of the different MCDMs are still the problem that reduce the reliability of the decision. For this, eight MCDMs which are Elimination and Choice Expressing Reality (ELECTRE) NI (Net Inferior), NS (Net Superior), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Vlekkriterijumsko KOMPromisno Rangiranje (VIKOR), Multi-Objective Optimization Ratio Analysis (MOORA), Weight Sum Method (WSM) and Weighted Product Method (WPM) are applied to select the heat mitigation measure under certain criteria. These models are also coupled to the AHP where the AHP method is used to determine the weights of the selected criteria and the operational MCDMs are used to obtain the final ranking of the alternatives. This numerical research evaluated the effectiveness of MCDM using different normalization techniques and the impact of their integrated model with AHP.

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# Chapter – 1

## Literature review

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This chapter is a state of art consist of following two parts:

- ❖ The part–A is the review on ambient air-cooling effect of green (vegetation), blue (water features) and grey (shading devices) interventions.
- ❖ The part–B is the detailed review on published studies on application of multicriteria decision making methods, developed toolkits and simulation tools in the field of mitigation of urban heat.

## Part - A

# Quantifying the Cooling Effect of Urban Heat Stress Interventions

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The **part–A** of this chapter has been accepted as “Quantifying the cooling effect of urban heat stress interventions” in last September and will be published soon on “International Journal of Global Warming”. The forthcoming article details are available at <https://www.inderscience.com/info/ingeneral/forthcoming.php?jcode=ijgw>

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### Major Findings

This review evaluates the existing studies of blue, green, and grey interventions based on field measurements and modeling aiming to quantify the cooling impact that reduces outdoor heat stress. Based on findings from literature, it is concluded that cooling effect of interventions depend on the site characteristics and local climate. However, water bodies can reduce the mean air temperature ( $T_a$ ) by 3.4°C and Universal Thermal Climate Index by 10.7°C, while natural vegetation can improve  $T_a$  by 2.3°C and Physiological Equivalent Temperature (PET) by 10.3°C during summer. Vertical greenery systems provide cooling effect of  $T_a$  up to 4°C, whereas architectural shades reduce it by approximately 3.8°C and PET up to 6.9°C under shade structure.

**Keywords:** Interventions; urban heat stress; urban heat island; mitigation; cooling effect.

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## 1.1 Introduction

Large-scale urbanization and the rapid population growth in big cities are contributing significantly to locally experienced impacts of climate change. Several heat-related issues have been reported globally, especially in Europe, and all countries have begun to pay attention to this problem and the adverse effects associated with it. One example is the Urban Heat Island (UHI) effect, a significant issue in hot summers, that affects the microclimate of the urbanized city, increasing the potential for warmer temperatures and where the air temperature ( $T_a$ ) in big cities remains higher with reference to the rural surroundings [1].

Human health is adversely affected by the increase in heat driven by climate change [2]. These effects are especially serious in summer for vulnerable groups such as the elderly, people with cardiovascular disease, and young children [3]. There have been particular events where the intensity of extreme heat has proven disastrous to human health, causing an increase in the mortality rate. The most common effects on the human health of the UHI and Urban Heat Stress (UHS) are heatstroke, dehydration, fainting, asthma, heat cramps, rash, skin allergies, physical and mental stress, and respiratory issues [4].

The urban infrastructure has a high thermal capacity allowing absorption of solar energy, causing a low evaporation rate and adversely affecting air quality for inhabitants [5]. The rapidly growing urban population has increased energy consumption by 75% resulting in energy dissipation as heat, which is further intensified by solar radiation. Surfaces such as roofs, pavements, and roads are composed of impervious, low albedo materials which tend to absorb and re-radiate a high amount of solar radiation in the infrared part of the spectrum. Air pollution and climate change are interlinked. The rapid growth in vehicle uses and fuel consumption is an additional contributor to the increase in temperature, with pollution from exhaust emissions increasing the adverse effects of UHI [6]. All these risk factors have focused the attention of researchers, urban planners, and society on developing appropriate strategies for mitigating UHS. Recent studies have evaluated the different techniques for mitigating the UHS effect which are mostly focused on the implementation and effectiveness of green roofs and cool materials [7], urban vegetation, watered cool pavements, water bodies, and shading canopies [8]. These interventions are used as the important resource to reduce heat stress through their cooling effect. There is an ongoing debate on the relative effectiveness of different interventions and this paper reviews both natural and

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built approaches by surveying peer-reviewed papers and evaluating them to identify the best strategies to mitigate UHS, particularly in summers when the heat island effect is greatest.

The objectives of this review are (i) to provide an overview of UHS mitigation strategies, (ii) to quantify the cooling effect of natural and constructed features based on different indicators, mainly  $T_a$  (iii) to analyze the results to determine the most efficient method to reduce UHS (iv) identify the co-benefits associated with these interventions.

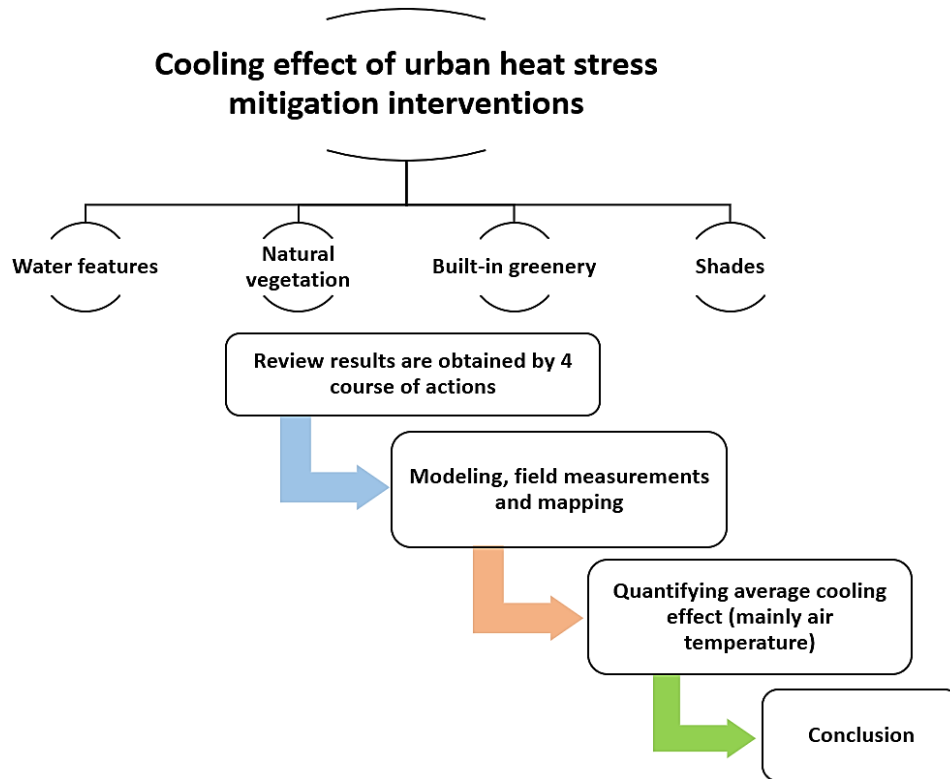
The methodology of this review paper is explained in section 2. The scientific works on which this article is based are summarized in the tables in section 3. The energy demand and costs/benefits of UHS and the UHI mitigation measures are briefly explained in section 4 and the results are discussed in section 5. Finally, a conclusion given in Section 6.

## **1.2 Methodology and Indicators of Cooling Effect**

This paper is a review of peer-reviewed articles on the cooling effect of various strategies. Among these, 24 articles studied water features, 31 green technologies, 13 shadings and 25 green vegetation. These studies were analysed and frequency of different indicators such as  $T_a$ , Universal Thermal Climate Index (UTCI), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Urban Heat Island Intensity (UHII), Mean Radiant Temperature ( $T_{mrt}$ ), Universal Effective Temperature (ETU), Surface Temperature of land and soil ( $T_s$ ), Pavement Heat Flux ( $PH_f$ ), Building Heat Flux ( $H_f$ ), Mediterranean Outdoor Comfort Index (MOCI), Wet Bulb Globe Temperature (WBGT), Relative Humidity (RH), Skin Temperature ( $T_{sk}$ ), Façade Temperature ( $T_f$ ), Park Cooling Intensity (PCI), Human Comfort Index (HCI), Globe temperature ( $T_g$ ), Black Globe Temperature ( $T_{gb}$ ) and Wall Temperature ( $T_w$ ) have been used to measure the cooling effect of blue, green and grey interventions that are graphically represented in the following sections. Among the numerous indicators used in past studies, this review is focused on the cooling difference in  $T_a$  because this was the most frequently used indicator for measuring the cooling effect.



The papers were selected on a random basis from across the world and published between 2006 and 2021. These studies involved field experiments, simulations, and modeling and most experimentally validated their simulations and models. The methodology is illustrated graphically in **Figure 1.1**.



**Figure 1.1: Methodological Framework of this Review Study**

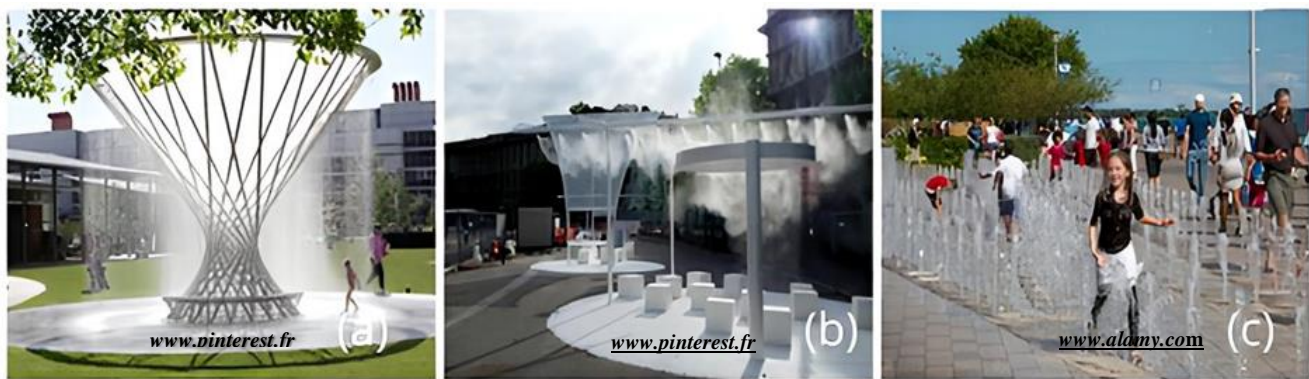
### 1.3 Interventions to Mitigate Heat Stress

Water features, vegetation, and constructed shade are also referred to as blue, green, and grey infrastructure respectively, and are among the most effective ways to provide cooling by evaporation and shading, and so improving the urban microclimate. Blue and green features have multiple additional environmental benefits, for instance ameliorating air quality and increasing biodiversity, particularly by means of urban vegetation, and are potent ways to combat UHS [9] and UHI. They are also beneficial in increasing thermal comfort in open spaces as well as compact and dense urban areas [10]. This paper

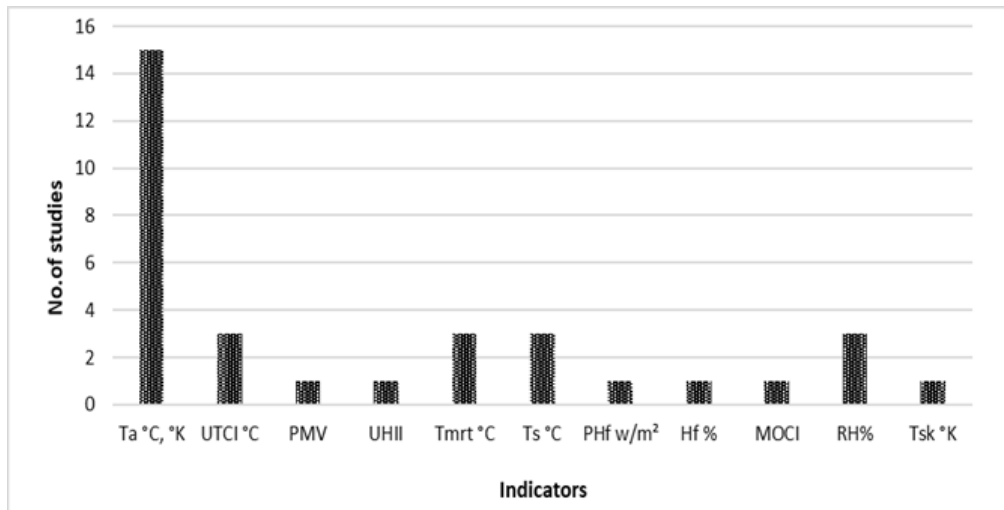
presents a review of interventions from across the globe, with the three categories, water features, green spaces, and constructed shade, described separately in the following sections.

### 1.3.1 Blue Infrastructure

Water areas, such as ponds, rivers, and lakes are known to significantly mitigating heat stress although cooling effect depends on the surrounding environment and atmospheric conditions [11]. This has led scientists to study interventions using water in different ways (shown in **Figure 1.2**) to reduce the environmental temperature [12]. **Figure 1.3** graphically represents the frequency of different indicators were used to evaluate the cooling effect of water features in selected papers.



**Figure 1.2: Images Showing Outdoor Interventions with Water Features. (A) Fountain Tree, (B) Water Misting System, (C) Little Water Fountains.**



**Figure 1.3: Measuring Parameters Used to Evaluate Cooling Effect of Water Features.**

### 1.3.1.1 Mistig Systems

One of the most attractive cooling methods is misting [13]. The effect has been measured by checking skin temperature ( $T_{sk}$ ) [14]. Most studies concerned with water features were carried out in an outdoor environment; the only exceptions where one installed on a station, and another installed indoors. This review has found two different types of misting systems; water misting [13] and dry misting [15]. The greatest cooling effect from a water mist cooling system was observed in a study from Atacama (Chile) which reduced  $T_a$  by 15°C [13].

### 1.3.1.2 Water Fountains, Water Pavements, and Water Sprays

Fountains not only minimize the effect of heat but also add aesthetic value to the surroundings, making them more pleasant and refreshing. Pavement watering has been studied for the past three decades and is considered one of the most effective techniques to improve thermal comfort. Watering surfaces can cool them to a certain extent, for instance watering pervious concrete material can reduce the  $T_s$  up to 2°C, while watering porous bricks can reduce the  $T_s$  by 20°C. If green areas in the urban landscape are combined with watering pavements this is particularly helpful in reducing the temperature during both the day and night [17].

Most research is conducted via simulations using Envi-met and Computational Fluid Dynamics (CFD) on models of water fountains along with water droplets, water jets, and water bodies. The addition of water jets showed a greater effect at night than during daytime. Fountains installed along with water bodies have been found to decrease the  $T_a$ ,  $T_{mrt}$  by increasing the humidity and cooling of the air [18].

### 1.3.1.3 Water bodies

According to research undertaken in Phoenix, Arizona (USA), the cooling effect of wetting streets, pond surfaces, and lakes was directly proportional to their surface areas, the larger the water body, the greater the cooling effect. The UHI mitigation depends upon the amount of water being used for the purpose [19]. Similarly, another study shows that the  $T_{mrt}$  of the asphalt surface was higher as compared to the temperature of the water body with significant cooling effect extending for around 0.5 metres. In contrast, other studies have found that open water surfaces can influence temperature causing it to rise. One author from the Netherlands concluded that water bodies can increase the daily maximum UHI by 95 percent at night and as, despite seasonal change water temperature remains high [20] due to the absorption of heat throughout the day. Other researchers also support this seasonal variation which has a high impact on warmer days, with water remaining warm in lakes and rivers which influences the surrounding temperature [21]. The papers reviewed regarding the outdoor cooling effects of blue infrastructure are summarised below in *Table 1.1*

**Table 1.1: Literature Reviewed Regarding Blue Infrastructure**

Symbol	Type of water feature	Measurement method	Location	Monitoring Time (Summer)	Cooling Effect	Indicator	Ref.
<b>a</b>	Water misting system (cloud droplet)	Field Measurements	Rome and Ancona (Italy)	Day	8.2 to 7.9°C	UTCI °C	[22]
<b>b</b>	A fountain of water spray	Field Measurements and CFD simulations	Rotterdam (Netherlands)	Day	5°C/7°C	$T_a$ °C/UTCI °C	[23]

<b>c</b>	Surfaces of ponds, wetting streets, and lakes	Field measurements and simulations	Phoenix (USA)	Night	0.15 to 0.82°C/hr	$T_a$ °C/hr	[19]
<b>d</b>	Water pond	Field measurements	Guangzhou (south China)	Day	1.5°C/increase 6%	$T_a$ °C/RH%	[24]
<b>e</b>	Water droplets around fountains	Simulations	Korea	–	0.5°C	$T_a$ °C	[25]
<b>f</b>	River	Measurements	Sheffield (UK)	Day (^)	1.5°C	$T_a$ °C	[21]
<b>g</b>	Water misting or micro water droplets	Measurements and CFD simulations	Tokyo (Japan)	Day	2°C	$T_a$ °C	[16]
<b>h</b>	Prototype water mist cooling systems	Measurements	Atacama (Chile)	Day	15°C	Overall (across universal thermal climate index (UTCI), $T_{mrt}$ and $T_a$ recordings)	[13]
<b>i</b>	Water pools and ponds	Measurements	London (UK)	mainly day	up to 7.1°K	$T_a$ °K	[26]
<b>j</b>	Dry mist	Measurements	Futamatgawa, Tokyo (Japan)	Day	1.63°K to 1.9°K	$T_a$ °C	[15]
<b>k</b>	pavement watering + urban green areas	Modeling and Simulations	Paris (France)	Day and night	1.1°C and 2.6°C	$T_a$ °C	[17]
<b>l, m</b>	Water fountains and water jets	Envi-met Simulated	Lebanon	Day and night	2°C and 4°C to 5°C	$T_a$ °C	[27]

<b>n</b>	Dry mist	Field measurements and CFD analysis	Japan	Day	3°C / increase 15%	$T_a$ °C / RH%	[16]
<b>o</b>	Fountains and water bodies	Envi-met Simulated	Alexandria (Egypt)	mid-day	2°C / increase 6% / 5.5°C / 1	$T_a$ °C / RH%, $T_{mrt}$ °C / Predicted mean vote (PMV)	[18]

Note: In this review, the effectiveness of most interventions presented was recorded in outdoor spaces in the summer; those also taken in winter are indicated by ~ and those in spring by ^.

### 1.3.2 Green Infrastructure

Green infrastructure refers to vegetation, such as trees, grass, and other plants and these interventions may be supported by constructed frameworks, for example, green façades and pergolas, which provide shade, or grown in containers, as in green walls shown in **Figure 1.4**.

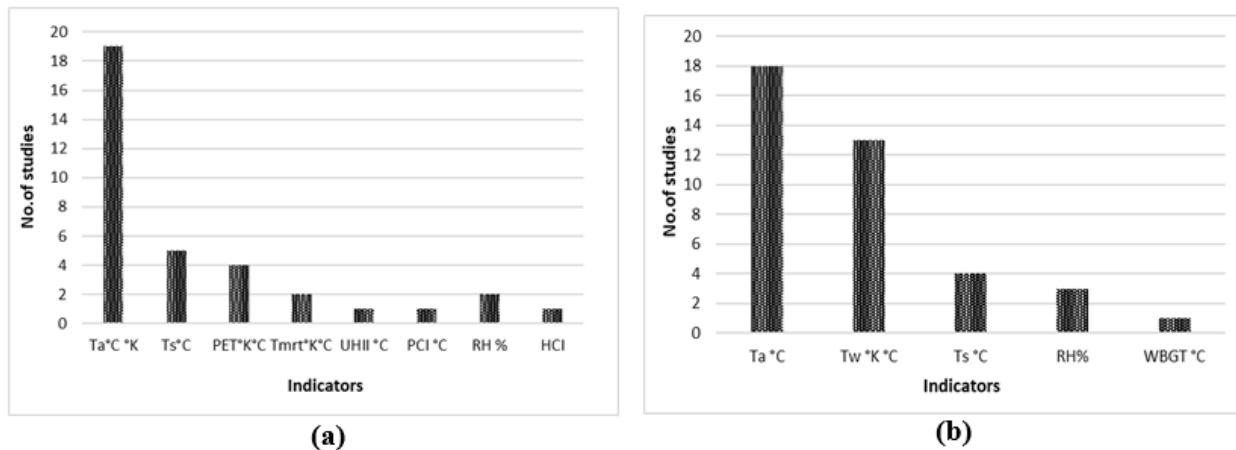


**Figure 1.4: Images Showing Outdoor Interventions with Green Infrastructures. (a) Green Shades, (b) People Enjoying Under Tree Shade, (c) and (d) Green Walls, (e) Living Wall and (f) Green Facade**

Trees can trap long-wave radiation significantly enabling pedestrians to walk comfortably in their shade. Grass and shrubs lower the  $T_s$  compared to other surface materials. Climate measurements made in the

centre of Athens (Greece) showed that the  $T_a$  of the green area is lower than the surroundings in the early morning [28]. Vertical green walls or green facades are approaches that can also ameliorate the thermal effect of urban areas.

This paper reviews research into the cooling effect of naturalistic greenery that is cheaper than constructed alternatives and can be implemented with less effort. During the screening of research articles, it was observed that different indicators have been used to quantify the cooling effect. The frequency of these indicators is graphically represented in **Figure 1.5** which shows that ambient air temperature is the most used indicator for quantifying the cooling effect.



**Figure 1.5: Frequency of Measuring Parameters used to Evaluate Cooling Effect of (a) Vegetation (Natural Green Infrastructure), (b) Supported Green Infrastructure.**

### 1.3.2.1 Types of Natural Green Interventions

#### (a) Grass

Researchers in Manchester (England) measured the difference in  $T_s$ ,  $T_a$  and demonstrated the cooling effect of grass [29]. Urban parks often combine dense vegetation along with water facilities [30]. Increasing the proportion of trees increases the cooling effect and humidity [31]. Grass alone can increase the RH [32] but this effect is greater when combined with trees [33]. A similar effect is observed with green or vegetated parking areas, where grass is grown in holes in paving or in a reinforcing mesh to

create a stable surface, but this provides less cooling compared to other vegetative paved surfaces due to the convention effect when cars are parked, and thermal energy is transferred, leading to  $T_a$  drop. Thus, vegetated pavement in parking areas lessens discomfort but not as much as installed at other situations.

**(b) Trees**

Trees are effective at absorbing and reflecting thermal radiation with the cooling effect depending on tree species and the planting pattern. The cooling effect of small leaved lime (*Tillia cordata*) was measured and an improvement in  $T_a$  was recorded during both day and night [34]. This suggests that an appropriate configuration of trees could provide a good cooling effect. Strategic placement of trees and green infrastructure has been found to not only reduce the UHI and UHS but also reduce premature human death during high temperature events [35].

Parks with a high density of trees experience reduced temperature and increased RH particularly during summer and can influence temperature and RH as far as 60 metre away [33]. Different numbers of trees have been compared and the most effective daytime cooling results were found with 50% tree cover [36]. In a study in Kaohsiung (Taiwan) 5 strategies were tested, the results showing that increasing the green coverage ratio (GCR) in the street up to 60%, in the park up to 80 %, and GCR on the roof of building up to 100% can reduce  $T_a$  [37]. The papers reviewed on the cooling effect of vegetation in outdoor spaces are given below in **Table 1.2**.

**Table 1.2: Literature Review of Natural Green Infrastructure**

Symbol	Natural Green Infrastructure	Measurement method	Location	Monitoring time (Summer)	Cooling effect	Indicator	Refs.
<b>a</b>	Grass	Experimental Measurements	Manchester (UK)	Day	up to 24°C / 0°C to 3°C	$T_s^{\circ}\text{C} / T_a^{\circ}\text{C}$	[29]
<b>b</b>	Green coverage (grasslands and broad-leaved trees)	Envi-met simulations	Freiburg (Germany)	Day	up to 43°K / 22°K / 3.4°K	$T_{mrt}^{\circ}\text{K} / \text{PET}^{\circ}\text{K} / T_a^{\circ}\text{K}$	[38]



<b>c</b>	Park grass	Experimental Measurements	Beijing (China)	Day	0.6°C / up to 2.44% / 1.00	$T_a$ °C / RH% / HCI	[32]
<b>d</b>	Parks with trees and grass	Meta-analysis (Studies)	–	Day	0.94°C	$T_a$ °C	[39]
<b>e</b>	Tree type <i>Tilia cordata</i>	Morphological Measurements	Munich (Germany)	Day and night	3.5°C and 0.5°C	$T_a$ °C	[34]
<b>f</b>	10% increase in vegetation	Field measurements	Shenzhen (China)	Day and night	0.05°C to 0.15°C and 0.16°C to 0.55°C	UHI (Difference of $T_a$ °C)	[40]
<b>g</b>	Tree shade	Field measurements and Simulations	Putrajaya (Malaysia)	Day	up to 2.7°C	$T_a$ °C	[31]
<b>h</b>	50% tree cover	Envi-met simulations	Cairo (Egypt)	Day	0.5°K to 1°K / 4°K	$T_a$ °K / PET°K	[36]
<b>i</b>	Green coverage ratio in street rises by 60% and park to 80 % set the GCR on the roof of building up to 100%.	Envi-met simulations	Kaohsiung (Taiwan)	Day	2°C	$T_a$ °C	[37]
<b>j</b>	Street trees	Envi-met simulations	Montreal (Canada)	Day	up to 0.3°C / 0.6°C to 2.1°C / 1.1°C to 3°C	$T_a$ °C / PET°C / $T_{mrt}$ °C	[41]
<b>k</b>	Leaf area index = 45 trees per hectare	Measurements and CFD modeling	Slovenia	Day	up to 4.8°C	$T_a$ °C	[42]
<b>l</b>	Parks	Measurements	Melbourne (Australia)	Day	1°C	$T_a$ °C	[30]

<b>m</b>	Urban parks (Tree shade)	Measurements	Taipei (Taiwan)	mid-day	0.64 to 2.52°C / 3.28°C to 8.07°C	$T_a$ °C / soil $T_s$ °C	[43]
<b>n</b>	Parking area with grass	Measurements	Kobe (Japan)	Day and night	0.1°C	$T_a$ °C	[44]
<b>o</b>	Strategic placement of trees	Studies analysis	UK	Day	2°C to 8°C	$T_a$ °C	[35]
<b>p</b>	Parks	Measurements	London (UK)	Night	1.1°C to 4°C	$T_a$ °C	
<b>q</b>	Parks with a high density of trees	Arc map	Lisbon (Portugal)	–	1°C to 3°C / 2% to 8%	$T_a$ °C / RH%	[33]
<b>r</b>	Green area	Measurements	Athens (Greece)	Morning	2°C	$T_a$ °C	[28]
<b>s</b>	Vegetation	Review study	–	Day	13°K	PET°K	[10]
<b>t</b>	Green ground	Envi-met simulations and measurements	Padua (Italy)	Day and night	3°C and 1.4°C	$T_a$ °C	[45]

### 1.3.2.2 Green Interventions Involving Support

#### (a) *Vertical Greening*

Vegetation that is supported by constructed frameworks or built structures to grow are referred to as Vertical Greenery Systems (VGS). In this study we considered two types of VGS; green façades, comprising climbing plants growing in the ground but supported on the walls of buildings [46], and green walls, which are vertical built structures consisting of containers of growth medium, such as soil or substitute substrate, in which the plants are grown, as well as an integrated hydration system. These types of greening offer numerous co-benefits, including aesthetics and biodiversity. An attractive solution is the application of vegetated facades, which help reduce heat by the phenomenon of

evapotranspiration as well as mixing air vertically, lowering the temperature in the surroundings and reducing UHI by providing fresh air [47].

**(b) Plant Species in vertical greening systems**

Different plants showed different efficiency, plants with woody branches and the smallest leaves appeared to be the most efficient in cooling effect during summer [48].

The efficiency in reducing  $T_s$  and  $T_w$  of species ranged from 1°C to 5.6°C, with Sword bean (*Canavalia gladiata*) the most efficient plant. In the UK, the cooling effect was considerable when the outdoor  $T_a$  evaluated with the extent to which temperature was affected different according to species [49]. Below are some reviewed studies for constructed greenery referring to cooling effects in outdoor spaces given below in **Table 1.3**.

**Table 1.3: Literature review of constructed green infrastructure**

Symbol	Constructed Green Technologies	Measurement method	Location	Monitoring time (Summer)	Cooling effect	Indicator	Refs.
a	Green wall and specially Stachys and Hedera	Measurements	UK	Day	3°C and special species up to 7°C	$T_a$ °C	[49]
b	Green wall/facade	Measurements	La Rochelle (France)	day and night	up to 4°C	$T_a$ °C	[50]
c	Green wall	Envi-met simulations	Colombo	Day	1°C to 2°C	$T_a$ °C	[51]
d	Green wall	Microscale modeling	Riyadh (KSA)	Day	up to 1.2°C to 9.3°C	$T_a$ °C	[52]
e	Vertical greenery systems	Measurements	Singapore	Day	3.3°C / 4 to 12°C	$T_a$ °C / $T_w$ °C	[53]
f	Vertical wall with green vegetation	Experimental measurements and C-M simulations	Thessaloniki (Greece)	Night	1.5°C / 0.58°C to 3.5°C	$T_a$ °C / $T_w$ °C	[54]

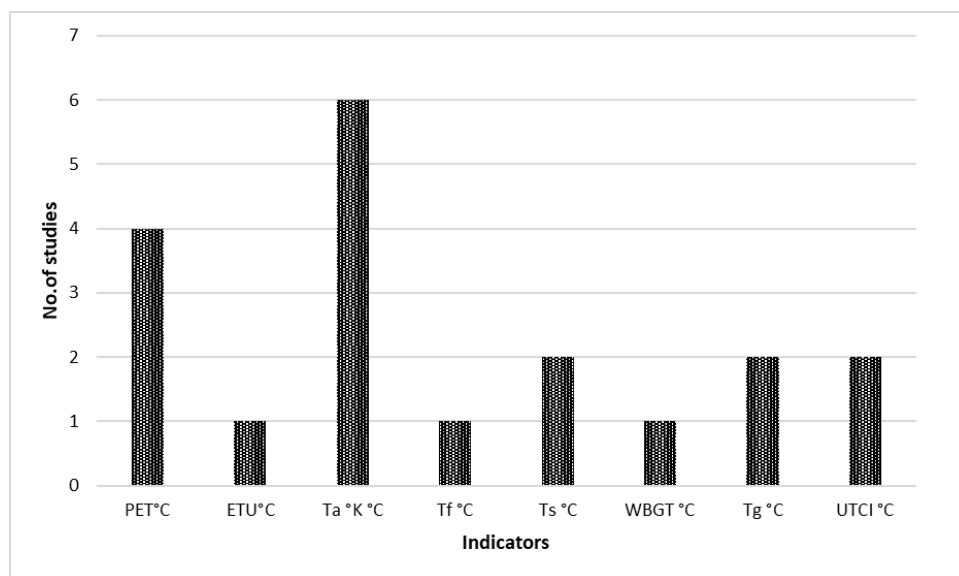
g	Green walls and green roofs	Measurements	Rio de Janeiro (Brazil)	Day and night	2.8°C to 8.1°C / increase 2%	$T_a$ °C / RH%	[55]
h	Vertical green wall	Measurements	Steinach am brenner and tyrol (Austria)	Day	0.9°C / increase 4.5% / 18.9°C	$T_a$ °C / RH% / $T_w$ °C	[56]
i	Green walls using <i>C. hyssopifolia</i> H.B.K species	Experimental measurements	Thailand	Day (~)	1.7°C	$T_a$ °C	[48]
j	Green facade	Measurements	Madrid (Spain)	Day	2.4°C to 2.9°C	$T_a$ °C	[57]
k	Vertical Green wall	Measurements	Shanghai (China)	Day	5.5°C	$T_a$ °C	[58]

### 1.3.3 Grey Infrastructure (Constructed shading)

Thermal stress in hot weather can limit outdoor activities. Outdoor spaces can be shaded in different ways; via shading devices [59], sun sails [60], architectural shading [61], shade pavilions or optimized awnings [62], parasols, deep canyons [63], textile canopies, and other overhead shade structures [64]. Some types of constructed shade can be seen in **Figure 1.6** and **Figure 1.7** graphically represents the number of times different parameters have been used to evaluate the cooling effect of constructed shading in papers.



**Figure 1.6: Images of Outdoor Grey Interventions (Constructed Shading). (a) Parasols, (b) Pavilion Shades (c) Green Pergolas**



**Figure 1.7: Measuring Parameters used to evaluate the Cooling Effect of Constructed Grey Infrastructure**

The papers reviewed s referring to cooling effects of shade structures in outdoor spaces is given below in *Table 1.4*.

**Table 1.4: Literature Review of Constructed Grey (Shades) Infrastructure**

Symbol	Type of Constructed shading	Measurement method	Location	Monitoring time (Summer)	Cooling effect	Indicator	Refs.
a	Optimized Awnings	Measurements	Central Italy	Day	2.5°C	PET°C	[62]
b	Sun sails	Measurements	Pecs (Hungary)	Day	5.8°C to 10°C	PET°C	[65]
c	Black and white sun sails	FEM simulations	Cordoba (Spain)	Day	up to 3°C / 12°C	$T_a / T_s$	[60]
d	Overhead shaded structures	Measurements	Milan (Italy)	Day	0.8°C / 6.1°C / 8.2°C / 5.3°C	$T_a$ °C / $T_{gb}$ °C / PET°C / UTCI°C	[64]
e	Architectural shading	Envi-met simulations	California (USA)	Day	1.6°C to 1.7°C	$T_a$ °C	[61]
f	Deep canyons	Measurements	Fez (Morocco)	Day	6°K to 10°K	$T_a$ °K	[63]

## 1.4 Energy-Saving Benefits of Interventions

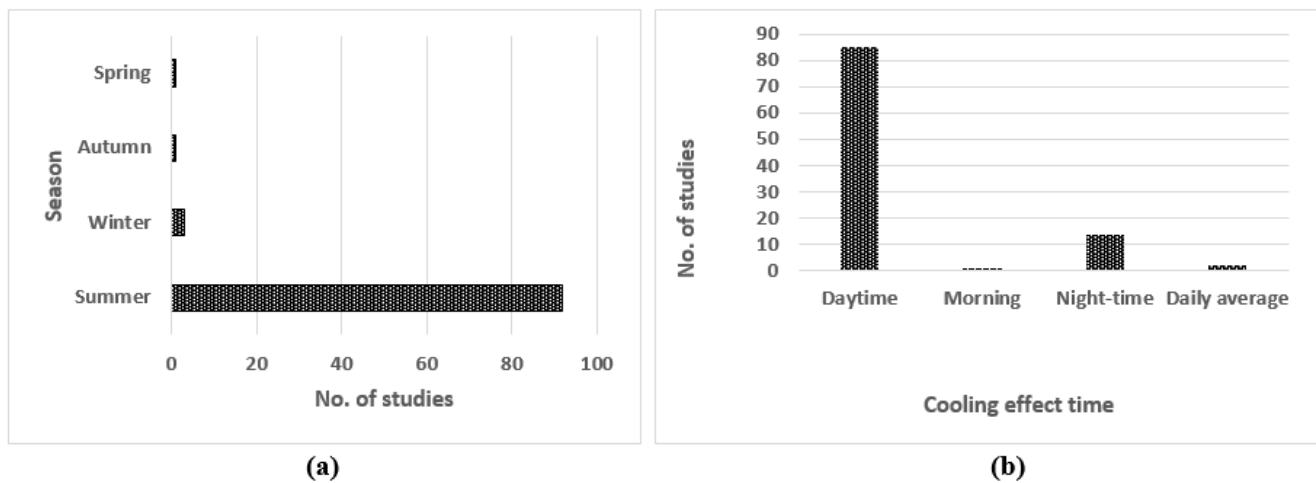
Nowadays, energy consumption is an important issue and the focus of attention for many scientists and researchers. For both cooling and heating, different technologies and electronic appliances are used, and various methods are applied by different countries in order to balance demand and consumption. The natural and constructed options discussed in this paper to improve thermal comfort in urban areas can reduce energy consumption, cost, and ultimately lead to sustainable city planning. Natural greenery reduces PET, particularly when combined with shading in summers [66]. Trees can decrease outdoor  $T_a$  and building cooling load by 29% [31] which ultimately reduces indoor air conditioning cost by around

25 Egyptian pounds, equivalent to 1.25 euro/day [36]. Another study showed that there was an annual saving of about 1.5 million US dollars because the urban forest, of about 100,000 trees, decreased the demand for energy and water [67]. Specifically in July, at the peak of summer, the installation of green facades can reduce building energy demand by up to 20% [68].

There are other shading technology options that not only provide pedestrian thermal comfort but also reduce energy demand. For an instance, the installation of sun sails in Mediterranean city streets can reduce cooling demand up to 46% [60]. Other shading devices in street canyons can reduce yearly heating load up to 18% during winter [69]. These interventions include green walls, suburban parklands and ceiling sprays [70] not only effective outdoor but also for the indoor environment.

## 1.5 Results and Discussion

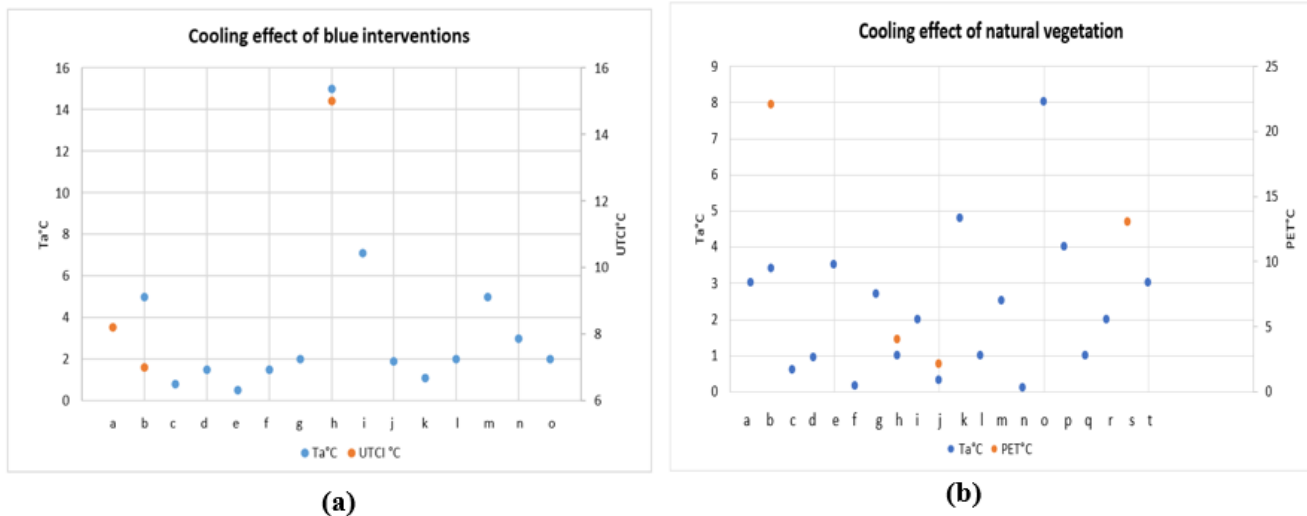
The overheating of urban areas has negative impacts on human health and contributes to increased morbidity and mortality in cities. Different interventions have been the subject of experiments and found to contribute to improving thermal comfort in outdoor open spaces, with most research conducted during the daytime in summer, as shown in *Figures 1.8(a) and (b)*.



*Figure 1.8: No. of Studies were Monitored in (a) Season and (b) Measurements Time.*

The literature on all four categories of interventions (water features, naturalistic and constructed green infrastructure, and shading) were carefully analysed, and cooling estimation for all categories of interventions are discussed as follows:

- ❖ **Blue infrastructure:** It has been found that mist nozzles are effective but need to be combined with fans to provide cooling relief. Spraying water on the pavement can cool by  $628 \text{ W/m}^2$  for  $1\text{mm/h}$  of sprinkled water due to evaporation, and  $12\text{--}18 \text{ W/m}^2$  of cooling for  $1\text{mm/h}$  due to advection. Water features are effective in reducing UHS by decreasing mean  $T_a$  by around  $3^\circ\text{C}$  and UTCI by up to  $10^\circ\text{C}$ . Thermal comfort achieved by different water features can be seen in **Figure 1.9 (a)**.

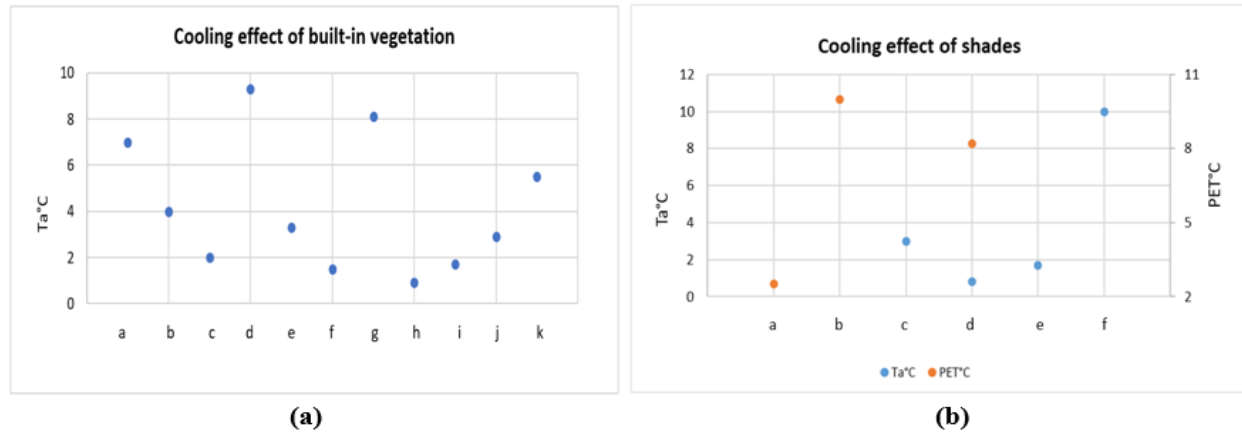


**Figure 1.9: Cooling Effect of (a) Blue Interventions and (b) Natural Green Interventions Achieved by Different Studies.**

- ❖ **Natural vegetation:** This can create have significant – and multiple - impacts on the environment. For example, measurements taken over grass alone were beneficial, but when combined with trees, showed a greater cooling effect. Grass contributed significantly to mitigating the UHS by reducing PET by at least  $10^\circ\text{C}$  while making a slight decrease in the  $T_a$  of approximately  $2^\circ\text{C}$ . Outdoor cooling effects of different type of natural vegetation are plotted in **Figure 1.9 (b)**.



- ❖ **Supported green infrastructure:** Green walls and facades improve both indoor and outdoor thermal comfort. The average air temperature ( $T_a$ ) can decrease by up to 4°C during the daytime in the summer season. Results of air cooling obtained by different studies are illustrated in **Figure 10(a)**.



**Figure 1.10: (a) Cooling Effect of Built-In Green Interventions Achieved by Different Studies, (b) Cooling Effect of Built-In Shades Achieved by Different Studies**

- ❖ **Grey infrastructure:** Sun sails and other shading device are beneficial due to their maximum cooling effect. Most studies support the idea that people prefer to walk on the streets because of overhead shading as it reduces the heat intensity [71]. The shades enhance pedestrian comfort in summer but during winter it causes cold stress and increases the heating requirement. Overall artificial shading structures provide a cooling effect with a decrease of the  $T_a$  by approximately 4°C and PET by 7°C. Results obtained with different types of shading are presented in **Figure 10 (b)**.

## 1.6 Conclusions

The reviewed interventions improve the thermal comfort and also have a positive psychological impact on citizens. When the environmental conditions are extreme with intense solar radiation, and heat levels rise, one must consider preventive actions and resources to implement cooling interventions in urban settings. When selecting the most appropriate heat resilience strategy, important criteria should be considered such as cooling effect, cost, maintenance, and public acceptance.

All the types of mitigation measures that are reviewed in this study provide cooling, but the effect depends on the local climate and geography. Future investigations should focus on developing a practical decision support tool that can help decision-makers to select an adaptation measure based on the characteristics of the proposed site, local social and economic circumstances, and constraints.

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## Part – B

# Review and Comparative Study of Decision Support Tools for the Mitigation of Urban Heat Stress

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The **part–B** of this chapter has been published as “Review and comparative study of decision support tools for the mitigation of urban heat stress” on “Climate” This paper is attached at *Paper - I* with kind permission from the journal and can be cited as:

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**Keywords:** Decision support tools; multi-criteria decision-making; heat stress; urban heat island

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### Major Findings

This review study based on Decision support tools have been developed to mitigate Urban Heat Stress (UHS) effects using nature-based solutions. It contributes to the UHS issue by: (i) identifying the most important key factors of a Decision Support Tool (DST) used for urban heat mitigation, (ii) presenting multi-criteria methods applied to urban heat resilience, (iii) reviewing existing spatial and non-spatial DSTs, (iv) and analysing, classifying, and ranking DSTs. The observation could help decision-makers through an overview of the pros and cons of existing DSTs and indicate which tool is providing maximum support for choosing and planning heat resilience measures from the designing phase to the heat mitigation phase. The obtained results shows that Multi-Criteria Decision Analysis (MCDA) can be used for any pilot site and the criteria can be adapted to the given location accordingly. It was found that GIS-based spatial tools have an effective decision support system (DSS) because they offer a quick assessment of interventions and predict long-term effects of urban heat. The tools were compared using 15 criteria which must be covered by the DST for eliminating risk of urban heat. It is concluded that despite many existing publications and reported tools, there is still room for improvement, which can be

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achieved by a holistic approach dealing with subjective and objective aspects of heat stress, combining various inputs from sensors as well as from experts and residents' feedback, and using different techniques such as MCDA, GIS, urban planning and, in the end, artificial intelligence tools to correlate these aspects with each other to develop a reliable DSS for the mitigation of heat stress.

## **Paper - I**

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# **Review and Comparative Study of Decision Support Tools for the Mitigation of Urban Heat Stress**

## Review

# Review and Comparative Study of Decision Support Tools for the Mitigation of Urban Heat Stress

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**Abstract:** Over the last few decades, Urban Heat Stress (UHS) has become a crucial concern of scientists and policy-makers. Many projects have been implemented to mitigate Urban Heat Island (UHI) effects using nature-based solutions. However, decision-making and selecting an adequate framework are difficult because of complex interactions between natural, social, economic and built environments. This paper contributes to the UHI issue by: (i) identifying the most important key factors of a Decision Support Tool (DST) used for urban heat mitigation, (ii) presenting multi-criteria methods applied to urban heat resilience, (iii) reviewing existing spatial and non-spatial DSTs, (iv) and analyzing, classifying and ranking DSTs. It aims to help decision-makers through an overview of the pros and cons of existing DSTs and indicate which tool is providing maximum support for choosing and planning heat resilience measures from the designing phase to the heat mitigation phase. This review shows that Multi-Criteria Decision Analysis (MCDA) can be used for any pilot site and the criteria can be adapted to the given location accordingly. It also highlights that GIS-based spatial tools have an effective decision support system (DSS) because they offer a quick assessment of interventions and predict long-term effects of urban heat. Through a comparative study using specific chosen criteria, we conclude that the DSS tool is well suited and fulfils many prerequisites to support new policies and interventions to mitigate UHS.

**Keywords:** decision support tools; multi-criteria decision-making; heat stress; urban heat island



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## 1. Introduction

Urbanization and an exponential increase in population have brought the concept of Urban Heat Island (UHI) and heat stress into the limelight. The world has seen adverse effects, particularly a rise in air temperature, a higher mortality rate, and changes in weather patterns [1]. Most studies have focused on the UHI in densely populated capital cities and there is insufficient literature available for smaller cities [2].

Different authors explained that UHI has severe effects on the most vulnerable populations, especially during the summer season. This phenomenon indeed highly raises the consumption of cooling energy as well as the corresponding peak electricity demand of cities. Therefore, the UHI can be linked with a significant increase in urban pollutant concentrations and is concerned with the city's carbon footprint as well as ground-level ozone. Urban Heat Stress (UHS) severely affects health, comfort, and increases mortality problems [3]. In current times, urban planners and policy-makers are keen to address issues such as increased urban heat due to climate change triggered by human activities.

Europe, Australia and North America are the major continents among those working to mitigate UHS in different ways, for example, by increasing urban forestry or by using green and blue interventions. On the other hand, Asia has also worked on thermal comfort but their focal point is grey and blue infrastructure. Accommodating heat stress measures in urban areas is not the easiest task as it encounters issues such as water scarcity, high cost and unsuitable environments for green infrastructure.

It is the responsibility of the decision-makers to evaluate multiple possible solutions to resolve the issues by considering specific criteria. Urban planners are still perplexed due to the severity of changes that have taken place in different zones.

Sometimes, alternative decisions are to be taken in order to combat the complex situation by considering some criteria [4]. It is observed in previous studies that every location has unique characteristics and parameters and the decision-makers have concerns about criteria such as cost, efficiency, and materials. For every location change, the mitigation measure should be modified. To solve these issues, a proper decision support system (DSS) is required to help decision-makers.

A DSS is an information system that requires judgment, determination, and a sequence of actions. It assists the mid-and high-level management of an organization by analyzing huge volumes of unstructured data and information. It is either human-powered, automated or a combination of both and it can be used in any domain due to its versatility.

There are many studies related to climate vulnerabilities—some have used economic or mechanistic modeling [5–7] and other researchers have used outranking approaches that later have been criticized due to axiomatic violations [8,9]. The number of characteristics required for the evaluation of UHS management similarly challenges is not constant. There is a need for a tool that allows one to work in consideration of all parameters simultaneously and helps to identify negative trends of urban heat and eventually allow better adaptation measures.

This paper presents a comprehensive review of DSTs in the essence of UHI, climate change adaptation, and heat stress. In Section 2, the methodology of the paper is discussed, Multi-Criteria Decision Analysis (MCDA) approaches are reviewed in Section 3, and DSTs (toolkits and spatial tools) are discussed in Section 4 of the research paper. All tools are critically analyzed by 15 important criteria in Section 5 and, finally, the conclusion is presented in Section 6.

## 2. Materials and Methods

### 2.1. Review Strategy

In this review article, we have used a qualitative and exploratory approach. Peer-reviewed research papers were gathered from Google Scholar. The research papers were selected by using keywords such as multi-criteria decision, UHI mitigation, heat resilience and UHS DST. Tools that are developed for urban heat resilience under the banner of different projects were searched by using the same keywords. The survey is presented in two tables. In the first table, we reviewed 9 academic studies in which different MCDA approaches were applied for developing DSTs for UHS mitigation. In the second table, we performed a review on different DSTs which deal with the UHI, climate change risks, extreme heat events, heat resilience adaptation and mitigation measures.

### 2.2. Inclusion and Exclusion Criteria

In this paper, we analyze 12 DSTs with the principle aspects to analyze the support of the decision-making tool, such as: (i) experts' assistance in the development of a support system; (ii) social culture factors, for example, number of population and their age, their activities, health data and the local environment; (iii) adaptive capacity of the tool which allows the indication of the suspect areas, informs where intervention is needed and when to schedule outdoor activities; (iv) good integration with other domains, which is correlated to a rise in UHS, can make the tool more advanced and gives a possibility to use the tool universally; (v) input requirements from the user, which means the decision results depend on the input data; (vi) indicator showing the vulnerability, heat events and effectiveness of the intervention; (vii) political and administrative support for developing the tool; (viii) vegetation, which is a basic and natural intervention that helps to reduce heat stress; (ix) graphical interface and heat stress visualization by mapping; (x) spatial coverage, which helps to indicate the suspect areas in a city on a GIS map; (xi) cost assessment of the measure; (xii) quick assessment of the intervention's effectiveness in real-time; (xiii)

user-friendliness, which shows how easy and difficult it is to use the tool; (xiv) uncertainty risk analysis, which gives trustworthy results; and (xv) plus points, which are when the tool provides a long-term effect of heat stress or considers other interventions apart from vegetation. These selected criteria were obtained after going through the literature and serve as a methodology, as shown in Figure 1.

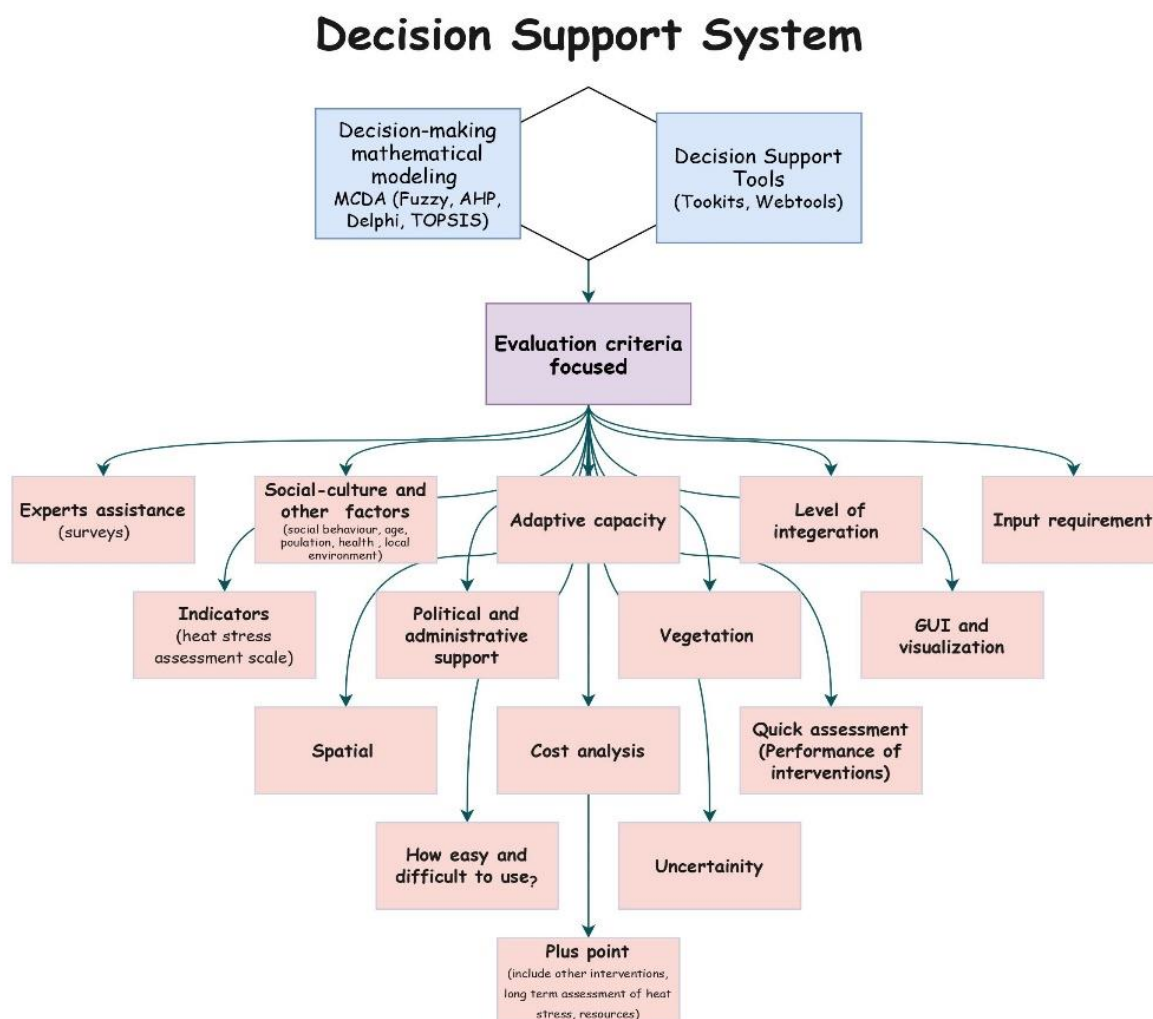
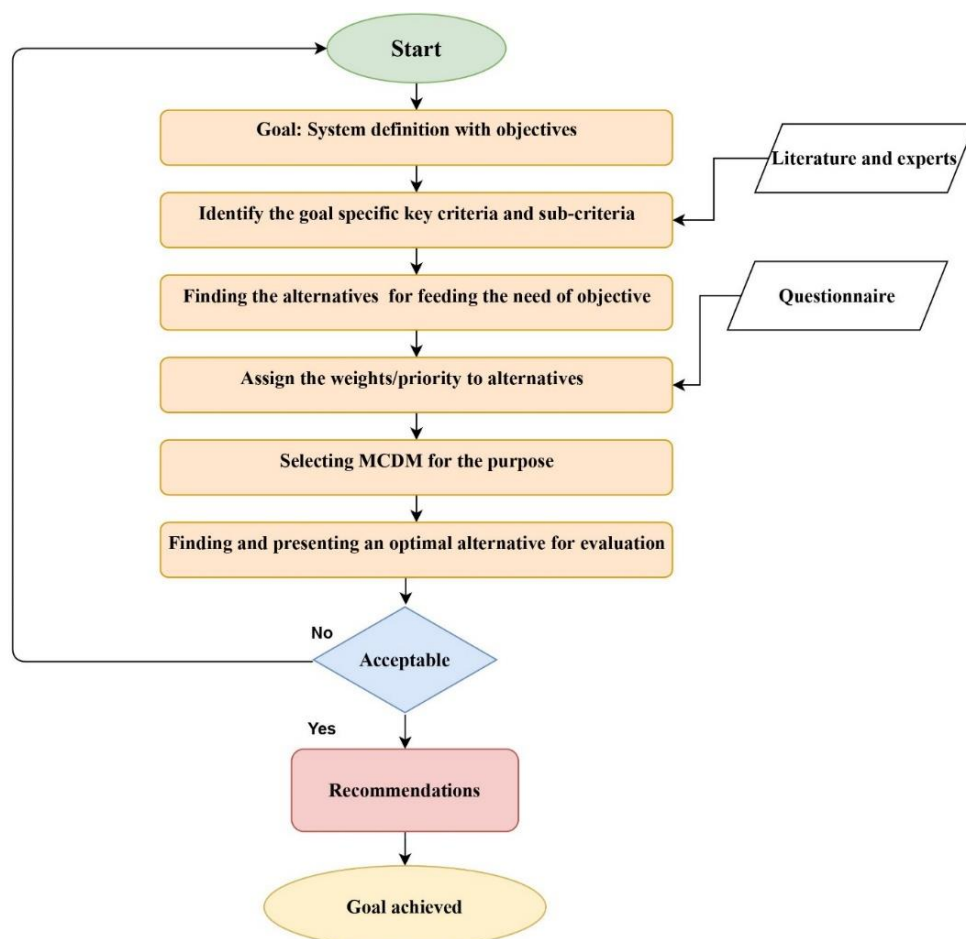


Figure 1. Methodology of the review paper.

### 3. Multi-Criteria Decision Analysis

Decision-making tools are valuable in tackling issues with numerous actors, criteria and objectives. Generally, MCDA is based on five components, which are: goals, decision-makers' preferences, alternatives, criteria and results, respectively. In light of many alternatives, differences can be catered between Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM), but both offer comparative characteristics. MODM is reasonable for the assessment of consistent options when there is a need to predefine constraints in the form of choice vectors. A set of target functions is optimized considering the limitations while decreasing the performance of at least one goal. In MADM, inherent characteristics are covered by prompting the thought of fewer options, and evaluation becomes difficult as prioritizing turns out to be more difficult. The result is obtained by comparing different alternatives concerning each criterion [10–12]. Different multi-criteria techniques are applied in the field of UHI mitigation, thermal comfort improvement, and the selection of the heat stress index. MCDA models are developed according to the researcher's point of view concerning demand and goal. It can

be a direct or indirect methodology. In a direct approach, the task of priorities or weights is performed as a result of contributions from a questionnaire. In an indirect approach, all the potential criteria are separated into components and assigned weights as per past comparable issues, and the judgment of decision-makers is based on experience. MCDA is consistently complex because of the involvement of stakeholders and factors which are technical, institutional, legislative, social and financial. The overall strategy of the MCDA technique is presented in Figure 2. A survey has been conducted on the use of different MCDA techniques for UHI and UHS mitigation.



**Figure 2.** A general procedure of multi-criteria decision methods.

The following methods were applied for UHS [3,13–20] and are briefly discussed with their limitations in Table 1.

- Analytical Hierarchy Process (SWOT);
- Multi-criteria outranking approach (MCDA and IBVA);
- Enhanced Fuzzy Delphi Method (EFDM);
- Fuzzy decision-making trial and evaluation laboratory (FDEMATEL);
- Multi-criteria method by linear regression;
- The technique for order of preference by similarity to ideal solution (TOPSIS);
- Spatial Multi-Criteria Evaluation (SMCE);
- Fuzzy Analytic Hierarchy Process;
- Fuzzy TOPSIS.



**Table 1.** Review of academic research on multi-criteria DST approaches for urban heat mitigation.

Aim of the Study	Method	Step	Limitation	Reference
Green roof adaptation in Thailand to mitigate UHI. The relevant factors were identified in qualitative content analysis, structured alongside two dimensions (internal/external and positive/negative factors), and quantitatively assessed.	Analytical hierarchy process based on expert judgments, strength, weakness, opportunities, threats (SWOT) analysis.	<ol style="list-style-type: none"> <li>1. Identification of initial factors (literature), investigation of contextual factors (semi-structured experts' interviews).</li> <li>2. Strength, weakness, opportunities, threats analysis (7 internal and 7 external factors).</li> <li>3. Analytical hierarchy process (AHP), experts' (academics, architects, landscape planners, and others) judgments and formulation of strategies.</li> </ol>	A limited number of factors considered and lengthy pairwise comparisons.	Tachaya Sangkakool [13]
Assess the heat stress relative vulnerability of 15 local government areas in metropolitan Sydney.	Multi-criteria outranking approach (build analogy between multi-criteria decision analysis and indicator-based vulnerability assessment (IBVA)). Electric III ranking process.	<p>Stage 1: Concordance and discordance matrices.</p> $c_i(a, b) = \begin{cases} 0 & \text{if } I_{ib} - I_{ia} \geq p_i \\ \frac{p_i - (I_{ib} - I_{ia})}{p_i - q_i} & \text{if } q_i < I_{ib} - I_{ia} < p_i \\ 1 & \text{if } I_{ib} - I_{ia} \leq q_i \end{cases}$ <p>Stage 2: Outranking matrix.</p> $C(a, b) = \frac{1}{\sum_{i=1}^m w_i} \sum_{i=1}^m w_i c_i(a, b)$ $S(a, b) = \begin{cases} c(a, b) & \text{if } d_i(a, b) \leq c(a, b) \forall i = 1, m \\ c(a, b) \prod_{i \in I_v(a, b)} \frac{[1 - d_i(a, b)]}{[1 - c(a, b)]} & \text{otherwise} \end{cases}$ <p>where <math>I_v(a, b)</math> is the set of indicators for which <math>d_i(a, b) &gt; c(a, b)</math></p> <p>Stage 3: Distillation and ranking procedures.</p> $T(a, b) = \begin{cases} 1 & \text{if } S(a, b) \geq \lambda - g(\lambda) \\ 0 & \text{otherwise} \end{cases}$ $Q(a) = \sum_{k=1}^m T(a, k) - \sum_{k=1}^m T(k, a)$	Nonlinearities might not be incorporated in the outranking aggregation process.	Abbas El-Zein [14]

Table 1. Cont.

Aim of the Study	Method	Step	Limitation	Reference
Investigate the inner-dependencies between the benefits, opportunities, cost, risks for proper adoption of green roof installation.	The enhanced fuzzy Delphi method (EFDM) and fuzzy decision-making trial and evaluation laboratory (FDEMATEL) approaches.	Step 1: Select the panel of experts. Step 2: Design and distribute the questionnaire. Membership function is:	Absence of significant relationships among environmental and economic opportunities.	Sanaz Tabatabaee [15]
		$\mu_{\tilde{A}}(x) = \begin{cases} (x-l)/(m-l) & , l \leq x \leq m \\ (u-x)/(u-m) & , m \leq x \leq u \\ 0 & , \text{otherwise} \end{cases}$		
		Step 3: Develop initial direct relation fuzzy matrix.		
		$\tilde{A}^{(s)} = \begin{bmatrix} 0 & \tilde{a}_{12}^{(s)} & \cdots & \tilde{a}_{1n}^{(s)} \\ \tilde{a}_{21}^{(s)} & 0 & \cdots & \tilde{a}_{2n}^{(s)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1}^{(s)} & \tilde{a}_{n2}^{(s)} & \cdots & 0 \end{bmatrix} \quad s = 1, 2, \dots, m$		
		Step 4: Normalize the initial direct relation fuzzy matrix.		
		$\tilde{E}^{(s)} = \begin{bmatrix} \tilde{e}_{11}^{(s)} & \tilde{e}_{12}^{(s)} & \cdots & \tilde{e}_{1n}^{(s)} \\ \tilde{e}_{21}^{(s)} & \tilde{e}_{22}^{(s)} & \cdots & \tilde{e}_{2n}^{(s)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{e}_{n1}^{(s)} & \tilde{e}_{n2}^{(s)} & \cdots & \tilde{e}_{nn}^{(s)} \end{bmatrix} \quad s = 1, 2, \dots, m$		
		Step 5: Develop the total direct and indirect relation fuzzy matrix.		
		$\tilde{O} = \tilde{E} \times (I - \tilde{E})^{-1}$		
		Step 6: Defuzzify the entries in the fuzzy total relation matrix.		
		$o_{ij} = (l_{ij} + 4m_{ij} + u_{ij}) / 6$		
		Step 7: Produce causal diagrams, values for D + R and D – R were calculated by the following equations:		
		$O = (o_{ij})_{n \times n}, i, j = 1, 2, \dots, n$		
		$D = \left( \sum_{j=1}^n o_{ij} \right)_{n \times 1} = (t_i)_{n \times 1}$		
		$R = \left( \sum_{j=1}^n o_{ij} \right)_{1 \times n} = (t_j)_{1 \times n}$		

Table 1. Cont.

Aim of the Study	Method	Step	Limitation	Reference
Identifying and assessing the critical criteria affecting decision-making for green roof type selection in Kuala Lumpur	An enhanced fuzzy Delphi method (EFDM) was developed for criteria identification. EFDM consists of two rounds: firstly, knowledge acquisition through a semi-structured interview, and secondly, criteria prioritization using a Likert scale questionnaire.	<ul style="list-style-type: none"> <li>First round: discuss the potential of criteria;</li> <li>Second round;               <ol style="list-style-type: none"> <li>Design the questionnaire and send it to the experts,</li> <li>Organize experts' opinions collected from the questionnaire into an estimate, and create the Triangular Fuzzy Numbers (TFNs),</li> <li>Select the criteria affecting decision making.</li> </ol> </li> </ul> <p><b>Fuzzy Delphi Method:</b></p> <ol style="list-style-type: none"> <li>Sets of pairwise comparisons according to the direction of influence of the relationship between the criteria/sub-criteria were generated. The comparison scale for pairwise comparison is 0, 1, 2, 3, and 4, which denote no influence, low influence, medium influence, and high influence, respectively.</li> <li>The direct-relation matrix was generated, which is the average of pairwise comparison matrixes that have been generated in step 1 by 28 experts. An <math>n \times n</math> matrix <math>A</math>, in which <math>A_{ij}</math> is the degree to which criterion <math>i</math> affects criterion <math>j</math>.</li> </ol>	If the expert decides to change an answer or decides to add any new information, the first round should be repeated, and the process will be time-consuming.	Amir Mahdiyar [16]
The study aims to map the UHI of a mid-size city (Rennes, France) and define the relevant land-use factors. The UHI was measured by 22 weather stations in different contexts: urban, suburban, and peri-urban.	Multi-criteria linear regression method used to build a model of the UHI.	<ol style="list-style-type: none"> <li>The first step of the process was to build a regression model by selecting explanatory variables;</li> <li>The second step of the process was to execute the selected regression during the first step;</li> <li>The regression coefficients were applied to the associated raster.</li> </ol>	Limited variables considered, do not provide reasoning and spatial method.	X. Foissard [17]

Table 1. Cont.

Aim of the Study	Method	Step	Limitation	Reference
Examines major local climate zones (LCZs), with greater coverage area, in the city of Nagpur, India by selecting critical LCZ and mitigation strategies such as greening, cool roof, and cool pavement using ENVI met tool. The study is conducted in three phases. The first stage deals with air temperature and UHI investigation. The second stage covers the issue of identifying criticality using multi-criteria decision making (MCDM) technique. The third stage examines the selection of mitigation strategies, simulation environment, and mitigation priorities.	The technique for order of preference by similarity to the ideal solution (TOPSIS).	<ol style="list-style-type: none"> <li>Construct decision matrix (X) and assign weightage to the criteria.  <math display="block">X = (x_{ij})</math> <math display="block">w = [w_1, w_2, \dots, w_n]</math> Considering <math>\sum_{j=1}^n w_j = 1</math> </li> <li>Calculate normalized decision matrix N.  <math display="block">N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}</math> for <math>i = 1, \dots, m; j = 1, \dots, n</math> </li> <li>Calculate weighted normalized decision matrix v.  <math display="block">v_{ij} = w_j N_{ij}</math> for <math>i = 1, \dots, m; j = 1, \dots, n</math> </li> <li>Determine the positive ideal (<math>A^+</math>) and negative ideal (<math>A^-</math>) solutions.  <math display="block">A^+ = (v_1^+, v_2^+, \dots, v_n^+) = \left( \left( \max v_{ij} \mid j \in I \right), \left( \min v_{ij} \mid j \in J \right) \right)</math> <math display="block">A^- = (v_1^-, v_2^-, \dots, v_n^-) = \left( \left( \min v_{ij} \mid j \in I \right), \left( \max v_{ij} \mid j \in J \right) \right)</math> </li> <li>Calculate the separation measures from the positive ideal solution (<math>d_i^+</math>) and the negative ideal solution (<math>d_i^-</math>)  <math display="block">d_i^+ = \left( \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \right)^{1/p}</math> <math display="block">d_i^- = \left( \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \right)^{1/p}</math> <math display="block">i = 1, 2, \dots, m</math> </li> <li>Calculate the relative closeness to the positive ideal solution (Performance Score) and rank the preference order or select the alternative closest to 1.  <math display="block">R_i = \frac{d_i^-}{d_i^- + d_i^+}</math> where <math>0 \leq R_i \leq 1, i = 1, 2, \dots, m</math> </li> </ol>	Quantitative analysis of urban geometric factors, street orientation, and thermal comfort and socio-economic condition assessments remain a limitation in this study.	Rajashree Kotharkar [18]
Spatial Multi-Criteria Analysis for Urban Sustainable Built-Up Area Based on UHI in Serang City.	Spatial Multi-Criteria Evaluation (SMCE) (utilizes software ILWIS (Integrated Land and Water Information System) 3.3 developed by ITC Netherlands).	UHI distribution, geometric correction, data processing, then simulations on SMCE model.	Does not consider the environmental factors (detailed challenges of UHI).	Putra Muhamad Iqbal Januadi [19]

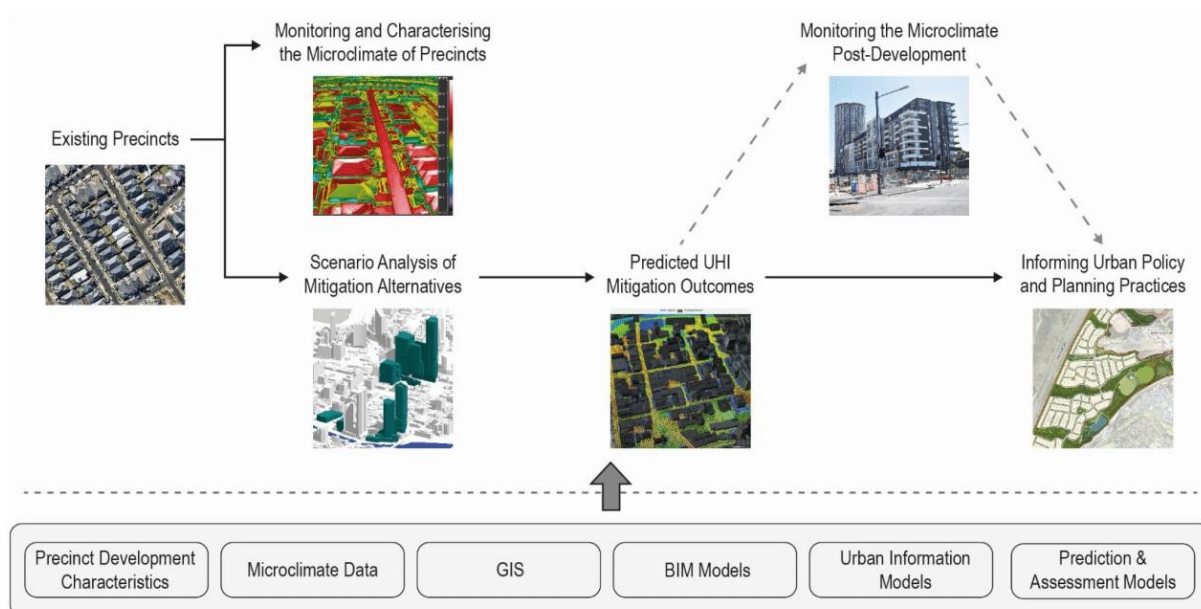
Table 1. Cont.

Aim of the Study	Method	Step	Limitation	Reference
An exhaustive study proposing a new index aimed at quantifying the hazard of the absolute maximum UHI intensity in urban districts during the summer season by taking all the parameters influencing the phenomenon into account. In addition, for the first time, the influence of each parameter has been quantified.	Results are achieved by exploiting three synergistically related techniques: analytic hierarchy processes to analyze the parameters involved in the UHI phenomenon; a state-of-the-art technique to acquire a large set of data; and an optimization procedure involving a Jackknife resampling approach to calibrate the index by exploiting the effective UHI intensity measured in a total of 41 urban districts and 35 European cities.	<ol style="list-style-type: none"> <li>1. The AHP step 1 consists of the Structure of the Problem to determine an index useful to quantify potential UHII in the urban district.</li> <li>2. The AHP step 2 is used to individually analyze each aspect of the defined UHII problem in order to weigh the parameters involved.</li> <li>3. The summary of priority is obtained by multiplying each criteria weight by the intensity range weight and adding the results.</li> </ol>	Based on literature quantitative analysis.	Sangiorgio [3]
Weighting Criteria and Prioritizing of Heat Stress Indices in Surface Mining.	<p>The viewpoints of occupational health experts and the qualitative Delphi methods were used to extract the most important criteria. Then, the weights of 11 selected criteria were determined by the Fuzzy Analytic Hierarchy Process. Finally, the fuzzy TOPSIS technique was applied for choosing the most suitable heat stress index.</p>	<ol style="list-style-type: none"> <li>1. The formation of implementing team and monitoring the Delphi process;</li> <li>2. Selecting the experts and participants;</li> <li>3. Adjusting the questionnaire for the first round;</li> <li>4. Editing the questionnaire grammatically (deductive and removing ambiguities);</li> <li>5. Sending the questionnaire to experts;</li> <li>6. Analyzing the obtained responses in the first round;</li> <li>7. Preparing the second-round questionnaire considering the required revisions;</li> <li>8. Sending the second questionnaire to the same experts;</li> <li>9. Analyzing the results of the second questionnaire;</li> <li>10. Determining the relative weights of each criterion using the fuzzy AHP;</li> <li>11. Choosing a heat stress index among the existing ones in the study using the fuzzy TOPSIS method.</li> </ol>	WBGT overestimates the heat stress.	Asghari [20]

#### 4. Decision Support Tools

From an environmental perspective, decision-making involves multiple complex steps for various stakeholders with different objectives and priorities. Most concerned people tend to attempt heuristic or intuitive approaches in order to simplify the problem to make it manageable. By following this approach, stakeholders lose important information and may discard the contradictory facts and factors of uncertainty and risks. In other words, it is not suitable for making thoughtful choices that can focus on all the important points of the process [21]. Therefore, a proper strategic decision-making tool is helpful to assess the decision-makers to bring about the process strategically and manage the multitude of ideas properly [22,23]. Additionally, during the process of decision-making, practitioners are supposed to take the elements of biodiversity, social innovation, governance, and urban management into consideration within a socio-ecological framework [24,25].

These tools are defined as an approach involving any techniques, models, frameworks (one project's framework can be seen in Figure 3), or methodologies that strategically manage and support the decision-making [26]. Moreover, decision-making tools help to evaluate and monitor the co-benefits systematically [27] and processes for connecting, reflecting and investigating, exploring, and modeling while suggesting proper solutions [28].



**Figure 3.** Framework of RP2023; Microclimate and Urban Heat Island Mitigation Decision-Support Tool [29].

One such example of these tools is the Adaptation Planning Support Tool (APST), which is specifically designed to focus on the impacts due to climate change. This toolbox has been proven to be useful for policy-makers and has been applied practically in many cities [30].

The Mitigation Impact Screening Tool (MIST) is another decision software-based tool developed by the US Environmental Protection Agency (EPA) for an assessment of the impacts of UHI mitigation strategies' (mainly albedo and vegetation) increase on the reduction in urban air temperatures, ozone, and energy consumption for over 200 US cities [31]. The tool is currently unavailable as it was disabled by the EPA due to the update of the methodology and data inputs. Nevertheless, some authors have analyzed how it functioned, as it attempted to provide a practical and customized assessment for UHI reduction.

Furthermore, there are various nature-based solutions and their implementation can offer multiple benefits, for example, Stadtklimatlotse, Wiki, REGKLAM, SUPER (Sustainable Urban Planning for Ecosystem Services and Resilience), and many more [32,33].

Table 2 represents the review of tools designed for policy-makers and urban planners to use during the process of decision-making for urban heat, climate change, heat vulnerability, health heat events, etc.

Table 2. Review of DSTs.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
<b>Stadtklimalotse (Urban climate pilot)</b>	Developed for urban planners and policymakers from small and medium-sized towns and cities who need quick and easy access to information.	Energy, health, tourism, water, infrastructure, transportation, green spaces, air quality, agriculture, forestry, heat stress.	Practice guides of 78 adaptation measures are available for resisting heat events, and among all only 3 are about green spaces in open public and private spaces; 330 links to legislative texts, and 61 examples for planning and implementation of heat stress measures.	German	<p>Online toolkit.</p> <ul style="list-style-type: none"> <li>Search ability of the entire database with a simple search mask.</li> <li>Does not attempt to make direct recommendations for action. Developed and published in 2013.</li> </ul>	-	Green spaces	Bundesinstituts für Bau-, Stadt- und Raumforschung (BBSR)—under different projects. (Germany)	[34]
<b>WBGT decision support tool</b>	High school athletes adjust practice schedules based on heat threat through the week	Heat stress	<ul style="list-style-type: none"> <li>Input data WBGT are temperature, dew point temperature, wind speed, relative humidity, pressure.</li> <li>Forecasting data from National Digital Forecast Database (NDFD).</li> <li>Past 24 h: Real-Time Meso-scale Analysis (RTMA).</li> <li>WBGT estimations are compared to measurements taken from Kestrels at 2 sites and an ExtechHT30 at 1 site.</li> </ul>	English	<p>Online tool</p> <ul style="list-style-type: none"> <li>Publicly accessible tool assesses hourly WBGT which helps to avoid heat stress exposure by making informed decisions about when to schedule outdoor activities.</li> <li>Provides guidelines for actions to take for WBGT risk categories.</li> <li>Spatial coverage is for North Carolina.</li> </ul>	WBGT	-	Collaboration between the State Climate Office of North Carolina, the SE Regional Climate Center, and the Carolinas Integrated Sciences and Assessments	[35]

Table 2. Cont.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
<b>California Heat Assessment Tool (CHAT)</b>	Target practitioners group includes local government such as urban planners, policy makers, public health associations and agencies.	Long-term public health impacts of extreme heat.	Meteorological dataset (minimum temperature (Tmin), maximum temperature (Tmax), minimum vapor pressure deficit (vpdmin), and maximum vapor pressure deficit (vpdmax)) for the years 1984–2013 were obtained from the PRISM Climate Group, and data were extracted at a daily time-step and at a resolution of 4 km. Analyzed historical medical and meteorological data and set a threshold for prediction mapping of heat health events (HHEs). Heat vulnerability data, solutions, publications are available.	English	Decision support user-friendly web tool. <ul style="list-style-type: none"> <li>Generates projected heat health event maps changing between 2011 and 2099. Helps to identify existing areas of need over 63 unique, health-informed heat thresholds tailored to California’s diverse tapestry of climates and demographics.</li> <li>Spatial coverage limited to California.</li> </ul>	Projected heat events, heat vulnerability, social vulnerability (% of outdoor workers, poverty, no health safety diploma, no vehicle access), health events (rate of asthma and cardiovascular diseases) environment (PM <sub>2.5</sub> concentration, ozone exceedance, UHI delta, % of tree canopy).	-	Four twenty-seven conducted UNA (California heat tool project)	[36,37]
<b>Right place—right tree</b>	For city officials as well as residents who are interested in expanding or maintaining Boston’s urban forest.	Informs decision-making for planting new trees for UHI mitigation.	<ul style="list-style-type: none"> <li>Provides full fact sheets that indicate the tree’s potential for heat reduction.</li> <li>Provides resources that can be consulted for maintenance of selected tree, includes links for contacting Boston’s tree maintenance teams, up-to-date information about pests, and tips for maintenance from the government website.</li> </ul>	English	Decision-making online tool for Boston only. <ul style="list-style-type: none"> <li>Highlights priority regions for canopy expansion indicating Boston-specific Heat Vulnerability Index (HVI), and summer daytime land surface temperature.</li> <li>Provides information in census tract, city, state, and federal owned properties, Boston housing and redevelopment authorities, and public land which may influence decision making.</li> </ul>	Summer morning land surface temperature, and heat vulnerability index.	Trees (33 species)	Supported by the BU URBAN Program, funded by a National Science Foundation Research Traineeship (NRT) grant to Boston University (DGE 1735087).	[38,39]



Table 2. Cont.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
Nature-based solution selection tool	Urban planners, municipalities	Challenges city is facing: Heat waves, biodiversity, flooding, public health and wellbeing, water quality, urban renewal, air quality and green space provision.	<ul style="list-style-type: none"> <li>Provides challenges and nature-based solutions catalog and gives recommendations for solutions of challenges with respect to users' input.</li> <li>Priority factors are evaluated through multiple criteria decision-making methods.</li> </ul>	English	<ul style="list-style-type: none"> <li>Decision support Excel toolkit.</li> <li>Provides decision interventions considering political and executive support, suitable internal regulation policy, staff time and motivation, advanced community management skills, alignment of internal departments and disciplines, culture of innovation and risk tolerance.</li> </ul>	-	18 green interventions and cool pavements	A toolkit developed under the project of URBAN Green Up funded by the European Union's Horizon 2020 program. Eight cities were involved in this project, including 3 European cities: Valladolid (Spain), Liverpool (UK), and Izmir (Turkey).	[40]
Adapting to the urban heat	Local government	Urban heat mitigation	Potential energy savings maps and thermal images of locations with and without interventions are presented to indicate benefits.	English	<p>DST in a detailed document.</p> <ul style="list-style-type: none"> <li>Explains how and when local government can adopt each method considering several criteria, including effectiveness at reducing heat, improving public health, saving money, and providing environmental co-benefits, and governance criteria including administrative and legal considerations.</li> </ul>	Benefits and co-benefits analysis.	Cool roofs, green roofs, cool pavements, and urban forestry.	Published by Georgetown climate center—A leading resource for state and federal policy (America).	[41]

Table 2. Cont.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
<b>Urban adaptation support tool</b>	Decision-makers, urban practitioners and municipalities	Climate change; heat waves, flooding, water scarcity, ice and snow, drought.	Step by step provides: links of Climate-ADAPT case studies of concrete examples from multiple European cities, guidance and tools relevant to local adaptation action, publications, reports and other Climate-ADAPT database resources, relevant EU-funded projects, Covenant of Mayors for Climate and Energy resources.	English	This tool is based on the adaptation policy cycle, assists cities with making climate strategy and offers valuable support in detailed guidelines and database through adaptation plans	-	Green spaces	Published and updated under European project	[42]
<b>Microclimate and Urban Heat Island Mitigation Decision-Support Tool</b>	Government municipalities, urban planners, and urban policymakers	Thermal comfort and vulnerability, UHI due to climate change	Fact sheets and publications and case studies are available.	English	<ul style="list-style-type: none"> <li>This spatial web tool for Sydney aims to integrate scientific models, performs and assesses evidence-based UHI mitigation strategies.</li> </ul>	UTCI	Vegetation, shading, water bodies, building coatings	Tool developed under the project named RP2023 was carried out by UNSW Sydney and Swinburne University in collaboration with government and industry partners.	[43]
<b>Climate Resilient city toolbox</b>	Urban planners, landscape architects	Heat stress, pluvial water safety, pluvial floods, and drought.	<ul style="list-style-type: none"> <li>Handbook for adaptation measures, description of adaptation key performance indicators, water balance model, and multi-criteria score tables of the selection tool in terms of suitability are available.</li> </ul>	Dutch	<ul style="list-style-type: none"> <li>Spatial web tool offers 18 adaptation measures for reducing heat stress and estimating the intervention's cost.</li> <li>Various plan alternatives (scenarios) can be quickly drawn up, compared with each other, and with previously set adaptation goals by this tool.</li> </ul>	PET °C	10 green and 7 blue interventions in different ways and 1 albedo.	The tool is developed by the cooperation of the following Dutch (Netherlands) partners: Deltares enabling delta life, Wageningen University and Research, Atelier Groen Blauw, TNO, Bosch Slabbers, Tauw and Hogeschool van Amsterdam.	[44,45]

Table 2. Cont.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
<b>Extreme Heat Map tool</b>	Urban planners, local government, community	Climate vulnerability assessment	<p>Tool based on:</p> <ul style="list-style-type: none"> <li>Land Surface Temperature layer is derived from data from Landsat 8 Thermal Infrared Sensor (TIRS) imagery taken during a heatwave in July of 2016.</li> <li>Other data include the 2016 Generalized Land Use and the 2015 Twin Cities Metropolitan Area 1m Urban Tree Canopy Classification.</li> </ul>	English	<ul style="list-style-type: none"> <li>Spatial web tool for Minneapolis indicates land surface temperature on GIS map, assesses the effectiveness of tree shades.</li> <li>Allows users to determine what land cover classes may contribute to mitigate the extreme heat.</li> </ul>	Land surface temperature.	Tree shades (Coniferous and Deciduous tree canopy and shrub wetlands).	Developed under Metropolitan Council local planning assistance (Minneapolis)	[46]
<b>Groen Tool</b>	City planners, planters, builders, designers, analysts, maintainers, etc.	Heat stress, air quality, water management, biodiversity, sound, CO <sub>2</sub> absorption, and recreation and proximity.	<ul style="list-style-type: none"> <li>Policy documents, practice booklet, literature and case studies, and plans are available on the website.</li> </ul>	Dutch	<ul style="list-style-type: none"> <li>Spatial Web tool for Antwerp.</li> <li>Calculate the adaptation measures' impact for the selected area.</li> <li>Effectiveness maps of green adaptive measures for all themes, i.e., heat stress, air quality, etc., with sub themes (e.g., air quality (PM<sub>10</sub> PM<sub>2.5</sub>, NO<sub>2</sub> and elemental carbon)) and indicates the high, medium and low risk areas.</li> </ul>	UH impact °C, average radiation temperature °C	Different green measures and their combinations.	The city commissioned VITO and Ghent University to develop this tool. (Belgium)	[47]

Table 2. Cont.

Tool Name	Users	Climate Change Fields of Actions	Database for UHS	Language	Tool Information	Indicator	Interventions for UHS	Projects	Refs
<b>Decision Support System (DSS)</b>	Urban planners, decision-makers and users who are interested in mitigating urban heat.	UHI mitigation	<ul style="list-style-type: none"> <li>Pilot (Bologna/Modena, Venice/Padua, Wien, Stuttgart, Lodz/Warsaw, Ljubljana, Budapest and Prague) simulations based on the data collected within the UHI project.</li> <li>Provides user-defined report in an Html page which comprises three primary components: a climate change assessment of the selected area, a set of normative data applicable to the selected area and skills, a bunch of potential mitigation strategies.</li> </ul>	English	<ul style="list-style-type: none"> <li>A free and user-friendly spatial database management tool but not open-source.</li> <li>Allows users to choose mitigation actions at building and urban scale and analyze the feasibility of the selected measures on an interactive map of central Europe.</li> <li>Provides economic assessment of chosen measures through online calculator.</li> <li>A set of maps shows change in the average annual mean temperature in every decade, changes in annual near-surface temperature during 2021–2050 and 2071–2100 and heat wave frequency during 1961–1990 and 2071–2100.</li> </ul>	Change in annual mean temperature and surface temperature, heatwave frequency.	<ul style="list-style-type: none"> <li>Cool roofs, green roofs, green facades, cool pavements, planting trees within the urban canyon and parks.</li> </ul>	Tool developed by UHI. The project was implemented through the Central Europe Programme co-financed by the European Regional Development Fund.	[48,49]

## 5. Results and Discussion

Multi-criteria mathematical models [3,12–19] are a valuable, theoretical, qualitative, and quantitative way of decision making and also a first step towards developing a DST. These models are supported by expert assistance which considers the socio-cultural factors and local environment. They cover the criteria which can be assessed statistically, e.g., cost analysis and political and administrative support.

The AHP is a qualitative approach and depends on the judgments of the people who are involved in the task, but lengthy pairwise comparisons might lead to inconsistency. Multi-criteria outranking is also controversial, and questions were raised about outranking procedures, nonlinearities' incorporation, and aggregation processes. Similarly, in FDE-MATEL, no significant relationships could be found for some criteria. Another issue is that the questionnaire can have a low response rate, be time demanding, and have a low probability of filtering out specific opinions.

Most of the time, this is a trial and error process.

Decision-making for urban heat mitigation involves multiple and complex steps that vary on different stakeholders with various adaptation measures and needs. Plus, during the process of decision-making, practitioners should take into consideration the criteria of biodiversity, social innovation, governance, and metropolitan management within a socio-ecological framework.

Some North American, European and Australian DSTs are critically analyzed concerning all the criteria which were considered in this review paper. The results are summarized and classified in Table 3. For future development, recommendations of approaches learnt from the surveyed tools are highlighted by a color-coding scale shown in Table 4.

The DSS [49] was developed in the framework of the European project “Development and application of mitigation and adaptation strategies for counteracting the global phenomenon UHI”. This tool is user-friendly and covers many aspects which are needed to support urban planners.

It is known that every testing (pilot) site is different depending on several factors such as climate, population, group of persons, building infrastructure, availability of existing interventions and number of heat events. The development of a DST depends on the scale of the project. Objectives and limited spatial coverage are always a drawback because all decision results are based on different pilot sites' data and tools are based on those characteristics.

**Table 3.** DSTs with respect to each criterion.

[illegible]

**Table 4.** Color code scale.

Color Codes	Explanation
	Covers all criteria (Highly recommendable)
	Covers 14/15 criteria (Highly recommendable)
	Covers 12/15 criteria (Strongly recommendable)
	Covers 11/15 criteria (Strongly recommendable)
	Covers 10/15 criteria (Recommendable)
	Covers 7/15 criteria (Slightly not recommendable)
	Covers 4/15 criteria (Not recommendable)

## 6. Conclusions

Decision-making is a difficult task that has to go through different phases such as identifying reliable and efficient measures, assessing the challenges to investigate the case studies, and building a systematic framework for decision support. The MCDA approach is a valuable and very important initial step to develop a DST to deal with UHS. Toolkits in the form of handbooks are neither spatial nor interactive. Web-based tools are mostly interactive and can provide an assessment of green, blue and grey interventions on heat impact in real-time and help decision-makers to take actions on the heat vulnerability of the suspected area. In these tools, economic and environmental assessment can be performed quite easily through a graphical interface; however, the results always depend on input data which are often difficult to obtain.

In this review and comparative study, we conclude that despite many existing publications and reported tools, there is still room for improvement, which can be achieved by a holistic approach dealing with subjective and objective aspects of heat stress, combining various inputs from sensors as well as from experts and residents' feedback, and using different techniques such as MCDA, GIS, urban planning and, in the end, artificial intelligence tools to correlate these aspects with each other to develop a reliable DSS for the mitigation of heat stress.

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# Chapter – 2

## Sensitivity Analysis of Heat Stress Indices

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This chapter is submitted as: **Sensitivity analysis of outdoor heat stress indices.**

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### Major Findings

More than 40 heat-indices are used across the world to quantify the outdoor thermal comfort. Several parameters including clothing, age, awareness, local environment, food consumption, human activities, and resources are relevant to select Outdoor Heat Stress Index (OHSI). This study was conducted to investigate (i) OHSI which are used to quantify the heat stress officially around the world (ii) Estimation method of indices (iii) Sensitivity analysis of indices namely Corrected Effective Temperature (CET), Heat Index (HI), Wet Bulb Globe Temperature (WBGT), Universal Thermal Climate Index (UTCI), Discomfort Index (DI), Summer Simmer Index (SSI) and Predicted Mean Vote (PMV). It has been observed that HI is a sensitive index for estimating heat stress. Conclusively, WBGT, HSI, and CET are recommended indices which can be directly measured using sensors instead of indices which are calculated using an estimation technique.

**Keywords:** Heat stress indices; sensitivity; variation coefficient; thermal comfort; public health

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## 2.1 Introduction

Heat stress refers to a discomfort condition that can be caused by long exposure to extreme heat [1]. It usually occurs when the body is unable to maintain a healthy temperature in response to a hot environment [2]. This effect may result in several negative impacts on public health and the quality of life in urban areas [3,4]. Major consequences of heat stress include heavy sweating, muscle cramps, unusual headaches, low productivity rate, etc. [5,6]. In addition, extreme heat itself can take a toll on the body and lungs. Breathing in hot and humid air can exacerbate respiratory conditions like asthma [7].

In different countries, heat stress is quantified with the help of specific indices. The thermal stress index is a quantitative measure that integrates one or more of the physical, thermal, and personal factors effecting heat transfer between the environment and a person [8]. Many heat stress indices have been developed and classified based on thermal comfort assessment, physiological strain, physical factors of the environment, and “rational” heat balance equation [9]. The thermal comfort of an individual depends mainly on the individual’s activities and other factors including behavioural activities, age group, health condition, and local climate and environment [10]. The collective factors are presented in **Table 2.1**. Individuals under high age group are generally more vulnerable to heat stress because of weak tolerance to bear extreme heat events and demand more comfort than young people [11].

**Table 2.1: Important Factors involve in Heat Stress**

Environmental	Physiological	Behavioural
❖ Air temperature	❖ Age	❖ Activity
❖ Wind velocity	❖ Gender	❖ Clothing
❖ Relative humidity	❖ Metabolism	❖ Insulation
❖ Mean radiant temperature	❖ Health status (Body	❖ Posture
❖ Globe temperature	temperature, rate of heartbeat,	
❖ Location	Blood pressure)	
	❖ Sweat rate	

Similarly, The rational heat measures are also dependent on heat stress [12]. The relation of the factors in **Table 2.1** helps to evaluate the heat stress vulnerability of the residents. To overcome heat stress issues, countries have adopted different techniques for the assessment of thermal comfort such as Wet Bulb Global Temperature (WBGT), Heat Stress Index (HSI), and Thermal work limit (TWL) which are the most popular indices and have been officially used by different countries' climate, environmental and national weather agencies [13]. Rising temperatures are more common in urban areas as compared to rural spaces. Most indices can be measured and calibrated directly by using equations whereas some secondary indices can be estimated by different methods and their models.

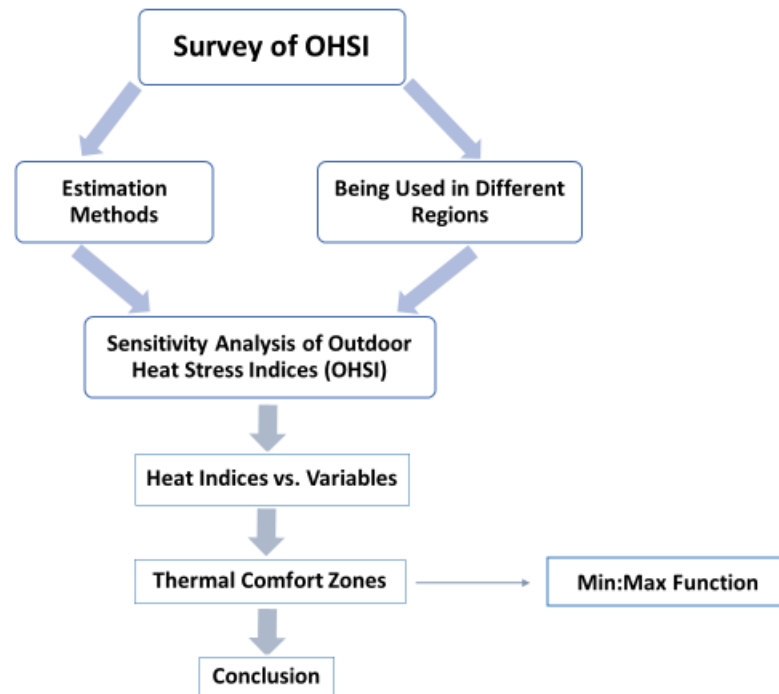
Current study aims to critically analyse the heat stress indices that are most commonly used nationally in different regions. The following tasks were investigated:

- ❖ Survey for Outdoor Heat Stress Indices (OHSI), officially used around the world.
- ❖ Estimation methods of heat stress and currently available modified thermal comfort scales.
- ❖ Sensitivity analysis of CET, HI, SSI, PMV, DI, WBGT, and UTCI.

The remainder of this paper is organized as follows: research methodology is presented in section 2, direct formulas for estimating different heat stress indices and methods for empirical indices are given in section 3, the survey map of OHSI used across the world by official agencies is presented in section 4, and results of sensitivity and thermal comfort scale variations are discussed in section 5. Finally, the conclusion and perspective are given in section 6.

## 2.2 Materials and Methods

The adopted methodology of current study is described in following **Figure 2.1**. The data was collected through OHSI survey. Following this, sensitivity analysis of OHSI was performed based on updated estimation models. Resultant models were computed for heat sensitivity indices vs. different variables to get the thermal comfort zones from the generated data using min:max functions. The overall findings along with computations has been provided in results section 5.



*Figure 2.1: A Schematic diagram showing the workflow of adopted methodology for sensitivity analysis of heat stress indices*

### 2.3 Estimation of Outdoor Thermal Indices

More than 40 indices have been used to quantify heat stress all over the world [14]. They are classified into three groups: “direct indices”, “empirical indices” and “rational indices”. Rational and empirical indices are very complex indices, evolving meteorological as well as physiological and behavioural factors of an individual making it difficult to estimate the thermal stress for an individual. In contrast, direct indices are simpler and can be monitored in outdoor and indoor environments by using different instruments or sensors like Kestrel [15], KIMO [16], and WBGT meter [17]. Calibration methods for popular and mostly used 16 outdoor heat stress indices are provided with their formulas in **Table 2.2**.

**Table 2.2 Outdoor Heat Stress Indices and Their Method for Estimation**

Heat stress indices	Formula	Nomenclature
WBGT: Wet bulb globe temperature [6]	$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$	
UTCI: Universal Thermal Climate Index [7]–[9]	calculated by 6 <sup>th</sup> order polynomial $UTCI = f(T_a; T_{mrt}; RH; v)$ $UTCI = 3.21 + 0.872T_a + 0.2459T_{mrt} - 2.5078v - 0.0176RH$	<ul style="list-style-type: none"> <li>• <math>C_{res}</math> = heat exchange by convection in breathing</li> <li>• <math>E_c</math> = heat exchange by evaporation on the skin</li> </ul>
HSI: Heat stress index [10]	$HSI = \frac{100Eq}{Emax}$	<ul style="list-style-type: none"> <li>• <math>E_{res}</math> = evaporative heat exchange in breathing</li> </ul>
Out_SET: Outdoor standard effective temperature [11]	$OUT\_SET = (WBGT - 11.76)/0.405$	
ESI : Environmental Stress Index [12]	$ESI = 0.62T_a - 0.007RH + 0.002.SR + 0.0043 \cdot (T_a \cdot RH) - 0.078 \cdot (0.1 + SR)^{-1}$	<ul style="list-style-type: none"> <li>• <math>Eq</math> = Required evaporative heat</li> </ul>
PMV : Predicted Mean Vote [13], [14]	$PMV = (0.303e^{-2.1 \times met} + 0.028) \times (met - mw) \underbrace{-H - E_c - C_{res} - E_{res}}_{\alpha}$	<ul style="list-style-type: none"> <li>• <math>Emax</math> = Maximum evaporative heat</li> </ul>
CET : Corrected Effective Temperature [15]	$CET = (1.21T_g - 0.21T_w) / (1 + 0.029(T_g - T_w))$	<ul style="list-style-type: none"> <li>• <math>H</math> = sensitive heat losses</li> <li>• <math>met</math> = metabolic rate</li> </ul>
DI : Discomfort Index [16]	$DI = T_a - 0.55(1 - 0.01RH)(T_a - 14.5)$	<ul style="list-style-type: none"> <li>• <math>T_{mrt}</math> = mean radiant temperature</li> </ul>
TSI : Tropical summer index [17]	$TSI = 1/3T_w + 3/4T_g - 2v^{1/2}$	

ECI : Equatorial comfort Index [18]	$ECI = 0.574T_a + 0.271vp - 1.81v^{1/2} + 4.2$	<ul style="list-style-type: none"> <li>• <math>mw</math> = effective mechanical power</li> </ul>
HU : Humidex [19]	$HU = T_a + (5/9)(e - 10)$	<ul style="list-style-type: none"> <li>• <math>RH</math> = relative humidity</li> </ul>
	$e = 6.11 \times e^{5417.7530 \times \left( \frac{1}{273.16} - \frac{1}{\text{Dewpoint in Kelvin}} \right)}$	<ul style="list-style-type: none"> <li>• <math>SR</math> = solar radiation</li> </ul>
SSI : Summer simmer index [20]	$SSI = 1.98(T_a - (0.55 - 0.0055 \cdot RH)(T_a - 58)) - 56.83$	<ul style="list-style-type: none"> <li>• <math>T_w</math> = wet-bulb temperature</li> </ul>
OI : Oxford index [21]	$OI = 0.85T_w + 0.15T_a$	<ul style="list-style-type: none"> <li>• <math>T_a</math> = air temperature</li> </ul>
ASV: Actual Sensation Vote value for Europe [22]	$ASV = 0.049T_a + 0.001 \cdot SR - 0.051v + 0.014 \cdot RH - 2.079$	<ul style="list-style-type: none"> <li>• <math>T_g</math> = globe temperature</li> </ul>
AT : Australian apparent temperature [23]	$AT = T_a + 0.33vp - 0.70v - 4.00$	<ul style="list-style-type: none"> <li>• <math>v</math> = wind speed / air velocity</li> </ul>
HI : Heat index [24]	$HI = -42.379 + 2.05 \cdot T_a + 10.14 \cdot RH - 0.22 \cdot T_a \cdot RH - 6.84 \cdot 10^{-3} \cdot T_a^2 - 5.48 \cdot 10^{-2} \cdot RH^2 + 1.23 \cdot 10^{-3} \cdot T_a^2 \cdot RH + 8.5 \cdot 10^{-4} \cdot T_a \cdot RH^2 - 1.99 \cdot 10^{-6} \cdot T_a^2 \cdot RH^2$	<ul style="list-style-type: none"> <li>• <math>vp</math> = vapor pressure</li> </ul>

**Important Remark:** Each heat index has different assumptions/calibrations (such as body size, physical fitness, etc.) that consider temperature and humidity differently. A high-heat-stress event indicated by one index does not necessarily transfer onto another index. For example, the original equation of WBGT was derived and calibrated using US Marine Corps Marines during basic training [37] and in good physical condition. HI was calibrated for an “average” American male [38]. We bring the attention of the reader to the only indices which can be measured using sensors i.e., CET, HSI, HI, WBGT, and

Thermal Work Limit (TWL). All other indices presented in **Table 2.2** are also estimated using their respective formulas or physical models which depend on assumptions e.g., age group, activities, clothing, area, etc. but cannot be directly measured.

## **2.4 Outdoor Heat Indices in Different Regions**

Local climate characteristics in regions (e.g., sub-tropical, tropical, Mediterranean) influence human thermal conditions and physiology. Many countries monitor heat stress using different parameters and estimates or measures through different indicators to inform locals about heat event warnings. Parameters like air temperature, relative humidity, and wind speed are helpful for the measurement of heat stress indices. WBGT is the most widely used index in different countries like Australia, U.S.A, Europe, Japan, and Columbia because it can be measured by sensors and estimated by a simple mathematical equation. The choice of the heat index depends on several factors of an area such as weather patterns (hot and dry, semi-humid and cold winter regions, etc.), age group of population (elderly, children, youth), activities, A limited survey study is being conducted to investigate the indices that are being used all over the world. The information of agencies officially involved in the assessment of heat is presented in Annex **Table A2.1** and the map shown in **Figure 2.2**. Countries highlighted in yellow on the map are using indices that can be measured using sensors.



## OUTDOOR HEAT STRESS INDICES OFFICIALLY USED AROUND THE WORLD

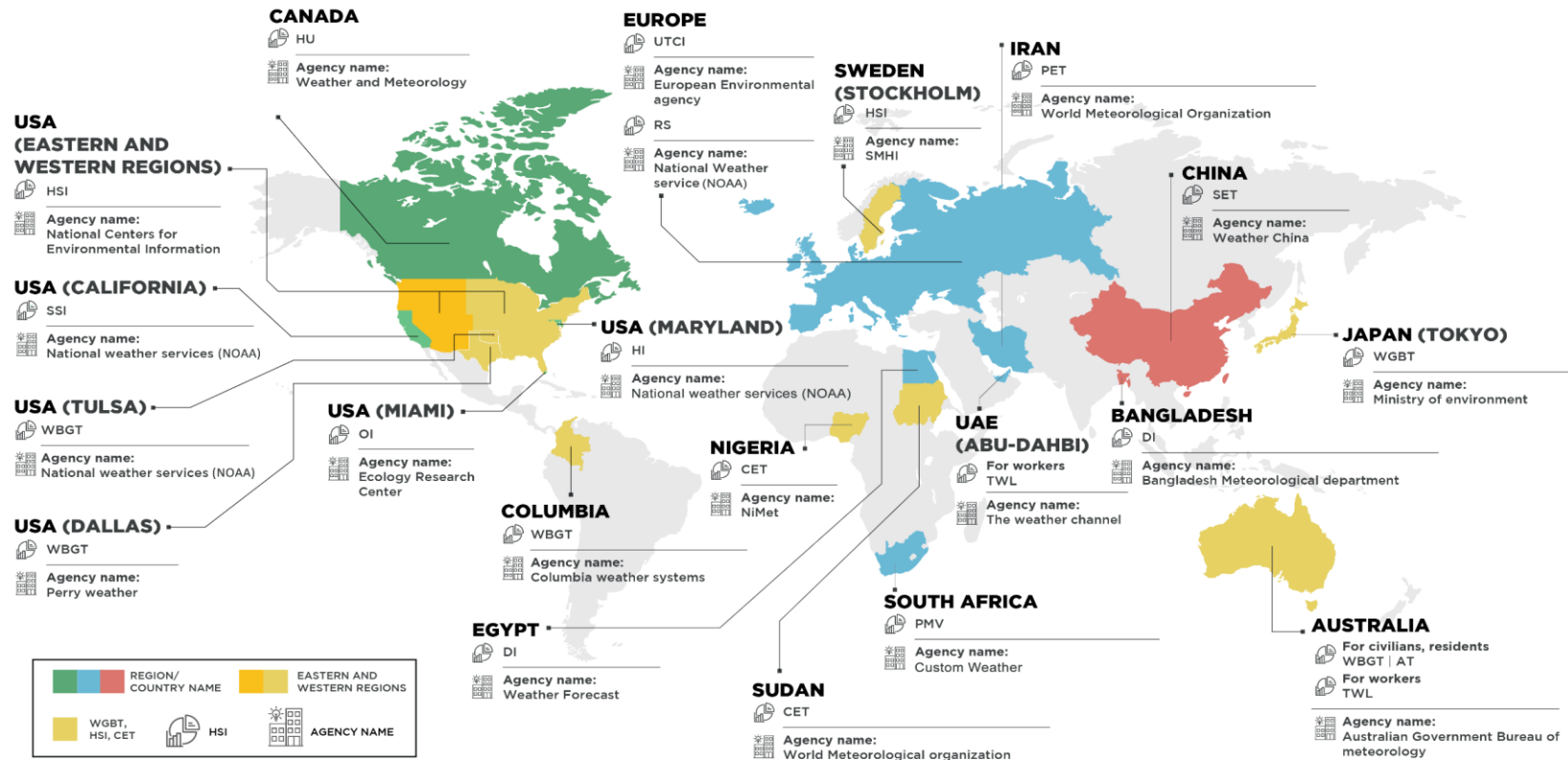


Figure 2.2: Map Showing Outdoor Heat Stress Indices Officially Used Around the World

## 2.5 Results and Discussion

### 2.5.1 Sensitivity Analysis of Heat Indices versus variables

In this section, we consider small variations (theoretically infinitesimal) around an operational point defined by a set  $S_0$  where the chosen values for the parameters involved in each index have been considered in a comfortable situation. A multi-variable partial differential equation is used for sensitivity analysis of the operational HS indices which are HI, WBGT, PMV, SSI, CET, DI, and UTCI.

**Table 2.3** gives the values for a set  $S_0$  which correspond to the comfort zone. For example, with  $T_{go} = 45^\circ\text{C}$  and  $T_{wo} = 16.27^\circ\text{C}$ , CET indicates comfortable conditions, however, small variations could lead to slight discomfort.

Subsequently, the sensitivity is computed in relation to small variations around the chosen reference values.

Consider a heat index  $y$  as a function of explicative variables  $x_1, \dots, x_n$  that is

$$y = f(x_1, \dots, x_n) \quad \text{eq: 2.1}$$

Where  $y$  (thermal index) is the function of  $x$  (input variables e.g.,  $T_g, T_a, T_{mrt}, RH, v, T_w, met, mw$ ).

Then a small variation of  $y$  can be expressed as

$$\Delta y = \left. \frac{\partial f}{\partial x_1} \right|_0 \Delta x_1 + \left. \frac{\partial f}{\partial x_2} \right|_0 \Delta x_2 + \dots + \left. \frac{\partial f}{\partial x_n} \right|_0 \Delta x_n \quad \text{eq: 2.2}$$

**Table 2.3: Sensitivity Analysis of Heat Stress Indices**

Heat stress indices	$S_0$	Sensitivity around $S_0$	Partial differential
CET	<ul style="list-style-type: none"> <li><math>CET_o = 27.83^\circ\text{C}</math></li> <li><math>T_{go} = 45^\circ\text{C}</math></li> <li><math>T_{wo} = 16.27^\circ\text{C}</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\left. \frac{\partial CET}{\partial T_g} \right _0 = 0.19</math></li> <li><math>\left. \frac{\partial CET}{\partial T_w} \right _0 = -0.08</math></li> </ul>	$\left. \frac{\partial CET}{\partial T_g} \right _0 = \frac{1.21[1 + 0.029(T_{go} - T_{wo})] - 1.21 \times 0.029 \times T_{go}}{[1 + 0.029(T_{go} - T_{wo})]^2}$

			$\frac{\partial CET}{\partial T_w} \Big _0 = \frac{-0.21[1 + 0.029(T_{g_0} - T_{\omega_0})] + 0.21 \times T_{\omega_0} \times 0.029}{[1 + 0.029(T_{g_0} - T_{\omega_0})]^2}$
PMV	<ul style="list-style-type: none"> <li><math>PMV_o = 0.379</math></li> <li><math>met_o = 1.68</math></li> <li><math>mw_o = 0.1</math></li> <li><math>\alpha = -0.33</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\frac{\partial PMV}{\partial met} \Big _0 = 3.6 \times 10^{-3}</math></li> <li><math>\frac{\partial PMV}{\partial mw} \Big _0 = -3.6 \times 10^{-2}</math></li> <li><math>\frac{\partial PMV}{\partial \alpha} \Big _0 = -0.33</math></li> </ul>	$\frac{\partial PMV}{\partial m} \Big _0 = \beta$ <p>where <math>\beta = -2.1 \times 0.303 \times e^{-2.1m_o} \times m_o + 0.303 \times e^{-2.1m_o} - 2.1 \times 0.303 \times e^{-2.1m_o} \times \omega_o</math></p> $\frac{\partial PMV}{\partial \omega} \Big _0 = -0.028 - 0.303 \times e^{-2.1m_o}$ $\frac{\partial PMV}{\partial \alpha} \Big _0 = -1$
HI	<ul style="list-style-type: none"> <li><math>HI_o = 78.74^\circ\text{F}</math></li> <li><math>T_{ao} = 81^\circ\text{F}</math></li> <li><math>RH_o = 30\%</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\frac{\partial HI}{\partial T_{ao}} \Big _0 = 1.71</math></li> <li><math>\frac{\partial HI}{\partial RH} \Big _0 = 0.32</math></li> </ul>	$\frac{\partial HI}{\partial T} \Big _0 = 2.049 - 0.22RH_o - 2(6.84 \times 10^{-3})(T_{ao}) + 2(1.22 \times 10^{-3})(T_{ao})(RH_o) + 8.5 \times 10^{-4}(RH_o)^2 - 1.99 \times 10^{-6}(T_{ao})(RH_o)^2$ $\frac{\partial HI}{\partial RH} \Big _0 = 10.143 - 0.22(T_{ao}) - 2(5.48 \times 10^{-2})(RH_o) + 1.22 \times 10^{-3}(T_{ao})^2 + 2(8.5 \times 10^{-4})(T_{ao})(RH_o) - 2(1.99 \times 10^{-6})(T_{ao})^2(RH_o)$
SSI	<ul style="list-style-type: none"> <li><math>SSI_o = 78.52^\circ\text{F}</math></li> <li><math>T_{ao} = 81^\circ\text{F}</math></li> <li><math>RH_o = 30\%</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\frac{\partial SSI}{\partial T_{ao}} \Big _0 = 0.89</math></li> <li><math>\frac{\partial SSI}{\partial RH} \Big _0 = 0.25</math></li> </ul>	$\frac{\partial SSI}{\partial T} \Big _0 = 1.98(0.45 + 0.0055RH_o)$ $\frac{\partial SSI}{\partial RH} \Big _0 = 1.98[0.0055T_{ao} - 0.0055(58)]$
DI	<ul style="list-style-type: none"> <li><math>DI_o = 20.24^\circ\text{C}</math></li> <li><math>T_{ao} = 27.22^\circ\text{C}</math></li> <li><math>RH_o = 30\%</math></li> </ul>	<ul style="list-style-type: none"> <li><math>\frac{\partial DI}{\partial T_{ao}} \Big _0 = 0.452</math></li> <li><math>\frac{\partial DI}{\partial RH} \Big _0 = 0.07</math></li> </ul>	$\frac{\partial DI}{\partial T} \Big _0 = 0.45 + 0.0055RH_o$ $\frac{\partial DI}{\partial RH} \Big _0 = 0.0055T_{ao} - 0.07975$

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WBGT	<ul style="list-style-type: none"> <li>• <math>WBGT_o = 23.11^\circ\text{C}</math></li> <li>• <math>T_{go} = 45^\circ\text{C}</math></li> <li>• <math>T_{\omega o} = 16.27^\circ\text{C}</math></li> <li>• <math>T_{ao} = 27.22^\circ\text{C}</math></li> </ul>	<ul style="list-style-type: none"> <li>• <math>\left. \frac{\partial WBGT}{\partial T_g} \right _0 = 0.2</math></li> <li>• <math>\left. \frac{\partial WBGT}{\partial T_w} \right _0 = 0.7</math></li> <li>• <math>\left. \frac{\partial WBGT}{\partial T_{ao}} \right _0 = 0.1</math></li> </ul>	$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$
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UTCI	<ul style="list-style-type: none"> <li>• <math>UTCI_o = 28.52^\circ\text{C}</math></li> <li>• <math>T_{ao} = 27.22^\circ\text{C}</math></li> <li>• <math>T_{mrt} = 27^\circ\text{C}</math></li> <li>• <math>v_o = 2 \text{ m/s}</math></li> <li>• <math>RH_o = 30\%</math></li> </ul>	<ul style="list-style-type: none"> <li>• <math>\left. \frac{\partial UTCI}{\partial T_{ao}} \right _0 = 0.87</math></li> <li>• <math>\left. \frac{\partial UTCI}{\partial RH} \right _0 = -1.76 \times 10^{-2}</math></li> <li>• <math>\left. \frac{\partial UTCI}{\partial T_{mrt}} \right _0 = 0.24</math></li> <li>• <math>\left. \frac{\partial UTCI}{\partial v} \right _0 = -2.5</math></li> </ul>	$UTCI = 3.21 + 0.872T_a + 0.2459T_{mrt} - 2.5078v - 0.0176RH$
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This study is relevant to know the trend of the variation and to exhibit the most sensitive parameters in the heat index:

- ❖ A positive sign means that the index increased with the parameter, whereas a negative sign means that the index increases (resp. decreases) when the parameter decreases (resp. increases).
- ❖ A high value of sensitivity means a high influence of the corresponding parameter on the given index.
- ❖ We can see that relative humidity has a negligible impact on DI and UTCI.

### 2.5.2 Variations of Thermal Comfort Zones versus Heat Indices

In this section, we analyse the influence of variables for widely used heat indices. More precisely, simulations have been performed for the parameter ranges for each thermal comfort zone defined according to the referenced *Table 2.4*.

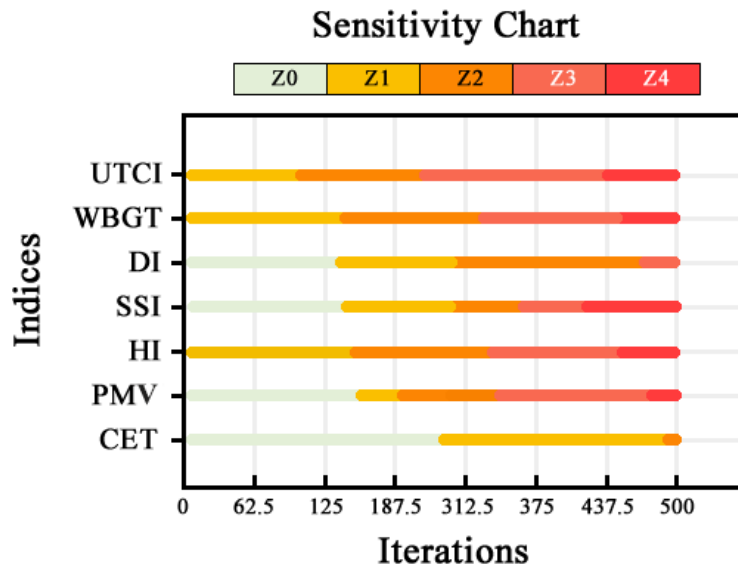
**Table 2.4: Reference Comfort Scale for Widely Used Thermal Stress Indices**

Comfort zone (Z)	WBGT °C	CET °C	UTCI °C	PMV	DI °C	SSI °F	HI °F
<b>Extreme cold stress (Z-5)</b>			<-40	-3 – -2.5			
<b>very strong cold stress (Z-4)</b>			-35 – -25				
<b>strong cold stress (Z-3)</b>			-25 – -13	-2.5 – -1.5			
<b>Moderate cold (Z-2)</b>	<17	<17	-13 – 0	-1.5 – -0.5			
<b>slightly cold (Z-1)</b>			0 – 8	-0.5 – 0			
<b>Comfortable (Z0)</b>		17-30	8 – 25	0 – 0.5		77– 83	
<b>slightly warm (Z1)</b>	17 – 23	30 – 34	25 – 31	0.5 – 1.5	22 – 24	83 – 91	
<b>moderate warm (Z2)</b>	23 – 28	34 – 45	31 – 37	1.5 – 2.5	24 – 28	91 – 100	80 – 91
<b>strong heat stress (Z3)</b>	28 – 30	45 – 49	37 – 46	2.5 – 3	>28	100 – 112	90– 105
<b>very hot (Z4)</b>	> 30		46 to above	3		112 – 125	105– 130
<b>extremely dangerous (Z5)</b>		>49		>3		125 – 150	>130

Formulas (*presented in Table 2.2*) are used to analyse the sensitivity of discomfort zones. The input mentioned in table 3 is used to simulate each index and it is observed that the HI, WBGT, and UTCI results are indicating a different comfort zone as shown in *Table 2.5* with colour codes. It is also noticed that due to the significant variation coefficient of HI, a small increase in its variables could lead to an increase in the level of discomfort while the results of other indices remain in the same comfort zone. Further,  $x_1, \dots, x_n$  are simulated by using the min-max function. Where  $x_{min}$  is the lowest possible ( $S_0$ ) and  $x_{max}$  is maximum possible value under the realistic situation in the summer season ( $T_g = 50, T_a = 50^\circ\text{C}, T_{mrt} = 50^\circ\text{C}, RH = 100\%, v = 10 \frac{m}{s}, T_w = 25^\circ\text{C}, met = 4, mw = 0.9, \alpha = -3$ ). At each time step only one variable was changing at the same time by 1. The obtained results are plotted shown in *Figure 2.3* which shows the sensitivity of thermal discomfort.

**Table 2.5: Sensitivity of Comfort Level**

Index	y	$\Delta y$
HI	78.74	80.78
SSI	78.52	79.67
PMV	0.37	0.29
WBGT	23.11	23.11
UTCI	28.52	28.52
CET	27.83	27.94
DI	20.24	20.76

**Figure 2.3: Thermal Comfort Scale Sensitivity Chart of Simulated Heat Stress Indices**

## 2.6 Conclusions

This study concludes that every region across the globe chooses heat indices according to some specific parameters. The factors that influence the selection are awareness among people especially vulnerable ones, physical interviews (knowing about the age, sex, sensations, clothing styles, and activities), the correlation between immune systems, and the number of heart-healthy events. Many

countries do not take much care of heat stress indices, are less focused on the resolution of climatic hazards, and fewer resources available for paying attention to environmental issues. Seven OHSI (CET, WBGT, UTCI, HI, DI, SSI, PMV) are programmed and simulated to analyse the variation coefficient of their evolving parameters. The results show that air temperature is the most sensitive parameter especially for estimating HI, SSI, DI, and UTCI whereas relative humidity is negligibly sensitive except in the case of SSI and HI.

In conclusion, we recommend the use of sensor-measurable indices such as WBGT, HI, and CET as they avoid errors that can occur with indices based on models that are only valid under certain assumptions that are difficult to realize in practice.

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## Annex

*Table A2.1. List of Outdoor Heat Stress Indices are officially used in Countries.*

Region/country name	TSI	Evolve Parameters	Sources	Agency name
<b>Columbia</b>	WBGT	$T_w, T_a, T_g, RH, v$	<a href="https://columbiaweather.com/products/weather-stations/wet-bulb-globe-temperature/">https://columbiaweather.com/products/weather-stations/wet-bulb-globe-temperature/</a>	Columbia weather systems
<b>Dallas</b>	WBGT		<a href="https://perryweather.com/weather-station/">https://perryweather.com/weather-station/</a>	Perry weather
<b>Tulsa</b>			<a href="https://www.weather.gov/arx/wbgt">https://www.weather.gov/arx/wbgt</a>	National weather services
<b>California</b>	SSI (Pacific Ocean and Mediterranean weather)	$RH, T_a$ in Fahrenheit	<a href="https://www.weather.gov/">https://www.weather.gov/</a>	
<b>Maryland</b>	Heat index (elder population)		<a href="https://www.weather.gov/safety/heat-index">https://www.weather.gov/safety/heat-index</a>	
<b>Miami</b>	Oxford Index	$T_w, T_a$	<a href="https://www.miamioh.edu/cas/academics/centers/erc/weather-station/index.html">https://www.miamioh.edu/cas/academics/centers/erc/weather-station/index.html</a>	Ecology Research Centre

<b>Eastern and western regions</b>	HSI	$T_a$ , RH, M, convective heat exchange, radiant heat exchange, $v$	<a href="https://www.ncdc.noaa.gov/societal-impacts/heat-stress/climatology">https://www.ncdc.noaa.gov/societal-impacts/heat-stress/climatology</a>	National Centres for Environmental Information
<b>Australia</b>	WBGT (for civilians)	$T_w$ , $T_a$ , $T_g$ , RH, $v$	<a href="http://www.bom.gov.au/">http://www.bom.gov.au/</a>	Australian Government Bureau of meteorology
	AT (for workers)	$T_a$ , RH, $v$		
	TWL	physiological data like height, age, sweat rate, $T_a$ , $T_w$ , $T_g$ .		
<b>Japan (Tokyo)</b>	WBGT	$T_w$ , $T_a$ , $T_g$ , RH, WS	<a href="https://mainichi.jp/english/articles/20180719/p2a/00m/0na/004000c">https://mainichi.jp/english/articles/20180719/p2a/00m/0na/004000c</a>	Ministry of environment
<b>Europe</b>	UTCI (semi humid hot summer and cold winter regions)	$T_a$ , average radiation temperature, WS, RH.	<a href="https://climate-adapt.eea.europa.eu/knowledge/european-climate-data-explorer/health/thermal-comfort-indices-universal-thermal-climate-index#details">https://climate-adapt.eea.europa.eu/knowledge/european-climate-data-explorer/health/thermal-comfort-indices-universal-thermal-climate-index#details</a>	European Environmental agency

	Required Sweating	RH, Sweat rate, M	<a href="https://www.weather.gov/oun/safety-summer-heathumidity">https://www.weather.gov/oun/safety-summer-heathumidity</a>	National Weather service (W.S)
<b>South Africa</b>	PMV (overrated summertime sensation and underestimated in winter)	$I_{cl}$ , M, RH, $T_{mrt}$ .	<a href="https://customweather.com/">https://customweather.com/</a>	Pietermaritzburg, South Africa
<b>China</b>	SET (subtropical regions)	RH, $v$ , M, radiation temperature, $T_w$ , $T_a$	<a href="http://en.weather.com.cn/">http://en.weather.com.cn/</a>	Weather China
<b>Sweden (Stockholm)</b>	HSI (elder population)	$T_a$ , RH, M, convective heat exchange, radiant heat exchange, WS	<a href="https://www.smhi.se/en/q/Stockholm/2673730">https://www.smhi.se/en/q/Stockholm/2673730</a>	SMHI
<b>UAE (Abu Dhabi)</b>	TWL (Occupational) for workers	physiological data like height, age, sweat rate, $T_a$ , $T_w$ , $T_g$ .	<a href="https://weather.com/weather/today/l/Abu+Dhabi+Abu+Dhabi+Emirate+United+Arab+Emirates?placeId=0755f9b1a0f85388ca0d9510010eed3e6274c95ec9ecc1a8353af4782d304238">https://weather.com/weather/today/l/Abu+Dhabi+Abu+Dhabi+Emirate+United+Arab+Emirates?placeId=0755f9b1a0f85388ca0d9510010eed3e6274c95ec9ecc1a8353af4782d304238</a>	The weather channels
<b>Bangladesh</b>	DI	$T_a$ , RH	<a href="http://live.bmd.gov.bd/">http://live.bmd.gov.bd/</a>	Bangladesh Meteorological department

<b>Egypt</b>	DI (hot dry climate)		<a href="https://www.weather-forecast.com/maps/Egypt">https://www.weather-forecast.com/maps/Egypt</a>	Weather Forecast
<b>Sudan</b>	CET	$T_g$ , $T_w$ , RH, $v$	<a href="https://worldweather.wmo.int/en/country.html?countryCode=203">https://worldweather.wmo.int/en/country.html?countryCode=203</a>	World Meteorological organization (M.D)
<b>Nigeria</b>	CET		<a href="https://www.nimet.gov.ng/">https://www.nimet.gov.ng/</a>	NiMet (M.D)
<b>Iran</b>	PET (hot dry climate)	$T_a$ , $v$ and $Mrt$ .	<a href="https://worldweather.wmo.int/en/country.html?countryCode=114">https://worldweather.wmo.int/en/country.html?countryCode=114</a>	World Meteorological Organization
<b>Canada</b>	HU (humid weather patterns)	$T_a$ , dew point temperature, RH factor, molecular weight of water, latent heat and gas constant.	<a href="http://ec.gc.ca/meteo-weather/default.asp?lang=En">http://ec.gc.ca/meteo-weather/default.asp?lang=En</a>	Weather and Meteorology. Retrieved May 19, 2016,

# Chapter – 3

## Heat Stress Modeling Using Neural Networks Technique

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This chapter has been published as “Heat stress modeling using neural networks technique” on journal “IFAC-Papers Online” This paper is attached at *Paper - II* with kind permission from the journal and can be cited as:

*Qureshi, A. M., & Rachid, A. (2022). HEAT STRESS MODELING USING NEURAL NETWORKS TECHNIQUE. IFAC-Papers Online, 55(12), 13-18. <https://doi.org/10.1016/j.ifacol.2022.07.281>*

**Keywords:** Artificial intelligence, thermal comfort, modeling, system dynamic approach and urban heat stress.

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### Major Findings

In this chapter effective and precise Heat Stress Assessment (HSA) is carried out using artificial intelligence (AI). The significant correlation with five most important meteorological parameters such as air temperature ( $T_a$ ), global radiation (GR), relative humidity (RH), surface temperature ( $T_s$ ) and wind speed ( $W_s$ ) is evaluated by system dynamic approach. and a new version of the Gated Recurrent Unit (GRU) method is used for the prediction of the mean radiant temperature, the mean predicted vote and the physiological equivalent temperature. New version of machine and deep learning approaches which are; Support Vector Machine (SVM) [1], Decision Tree (DT) [2], Random Forest (RF) [3], Long Short-term Memory (LSTM), simple Recurrent Neural Network (RNN) [4] and Gated Recurrent Unit (GRU) are used to predict outputs: mean radiant temperature ( $T_{mrt}$ ), Predicted Mean vote (PMV) and Physiological Equivalent Temperature (PET) using input variables ( $T_s, T_a, GR, RH$  and  $W_s$ ) for the

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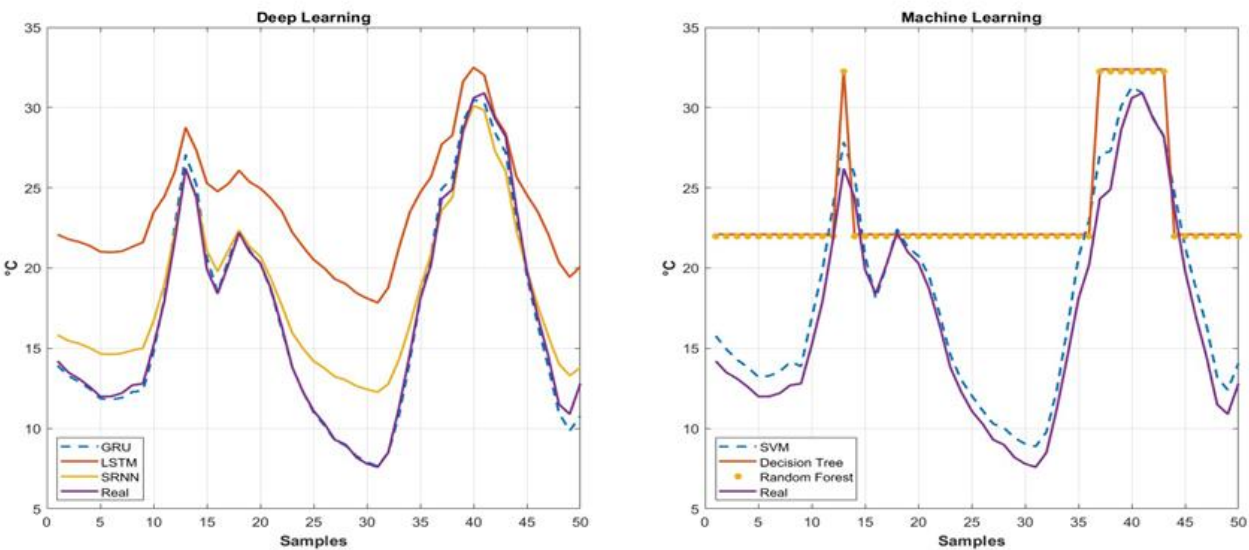


estimation of heat stress. Comparative analysis of obtained results showed that SVM is efficient approach, but GRU is most reliable and accurate with high testing efficiency among other used algorithms for dealing with weather data and estimate thermal comfort level. The applied algorithms' performances are presented in **Table 3.1**. The output of testing samples achieved from each model are plotted shown in **Figure 3.1**. It is observed that GRU is a promising and efficient technology, the results with higher accuracy are obtained from this algorithm. The results obtained from the model are validated with the output of reference software named Rayman. After validation the GRU model was adapted for the development of the user's friendly tool for HSA which allows users to select the range of thermal comfort scales based on their perception and will allow developer to use the database for further research. The colour codes warn the user about the level of discomfort which could help users to schedule and manage their outdoor activities.

**Table 3.1: Algorithms Performance with Respective Data**

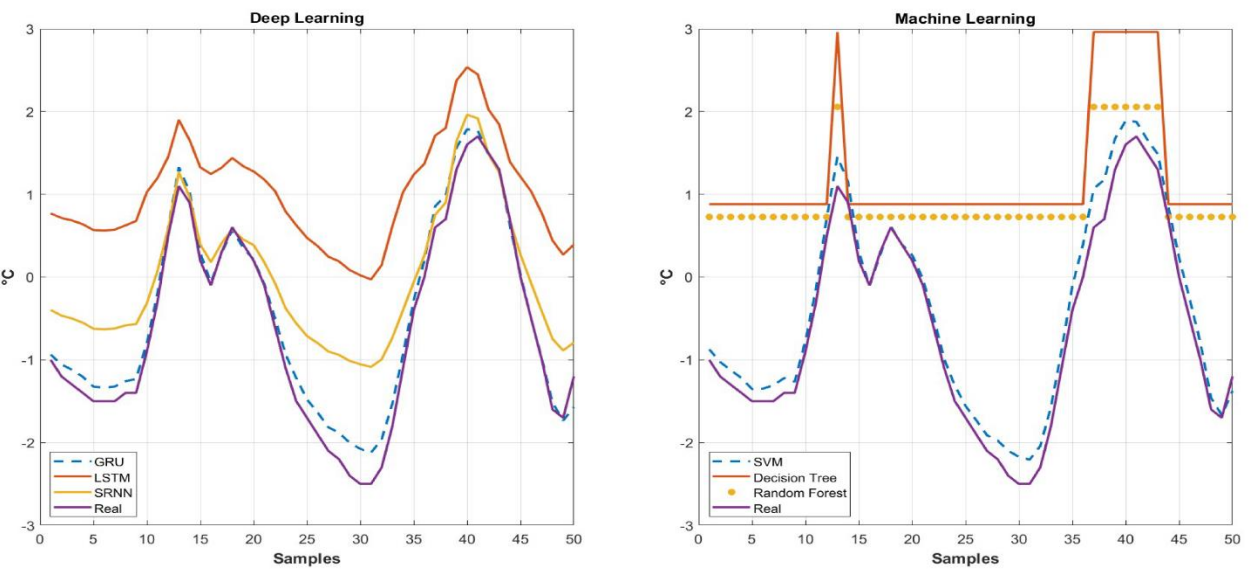
<b>Machine Learning</b>				
<b>Model name</b>	<b>Training efficiency (%)</b>	<b>Testing efficiency (%)</b>	<b>MSE train</b>	<b>MSE test</b>
Decision Tree	86.21	28.80	0.02	0.43
Random Forest	87.12	33.23	0.019	0.4
Support Vector Machine	98.54	98.52	0.00043	0.00077
<b>Deep Learning</b>				
Long Short-Term Memory	84.93	55.38	0.0047	0.012
Simple Recurrent Neural Network	97.49	88.16	0.00081	0.0035
Gated Recurrent Unit	99.34	99.04	0.00022	0.00028

PET

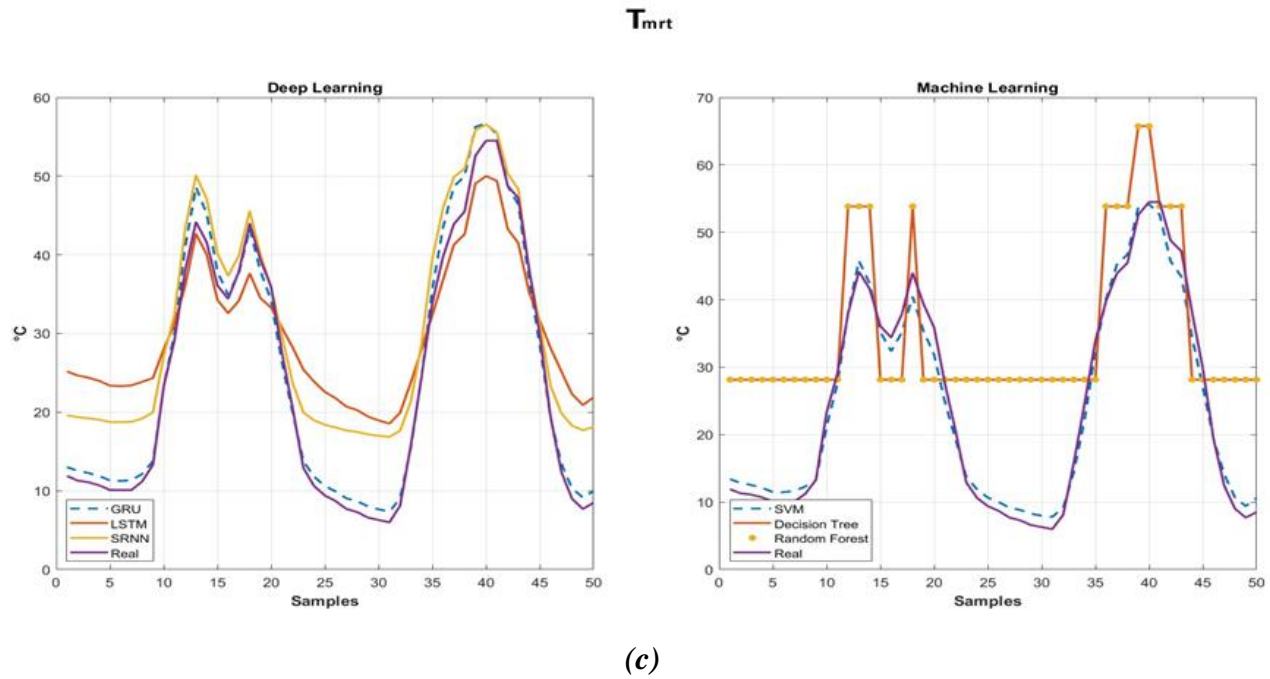


(a)

PMV



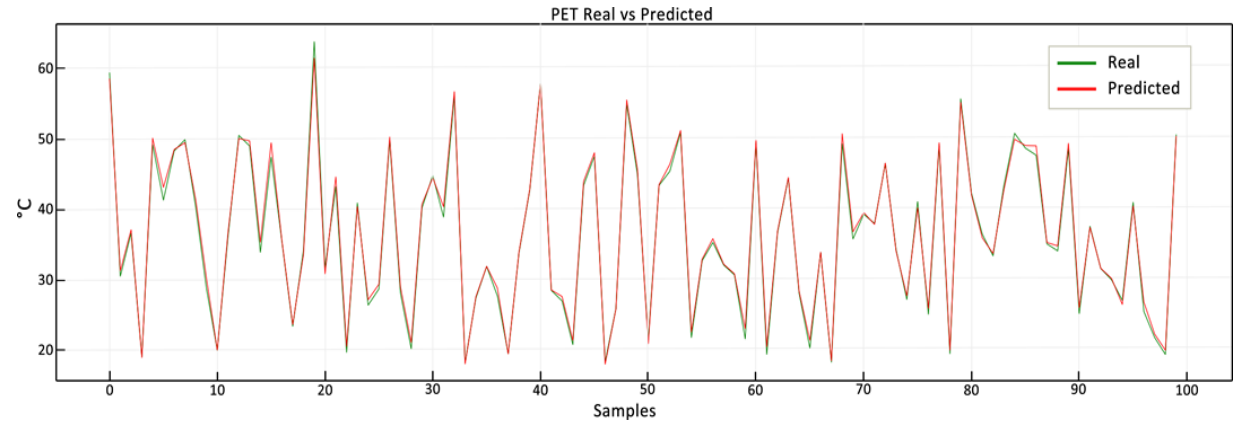
(b)



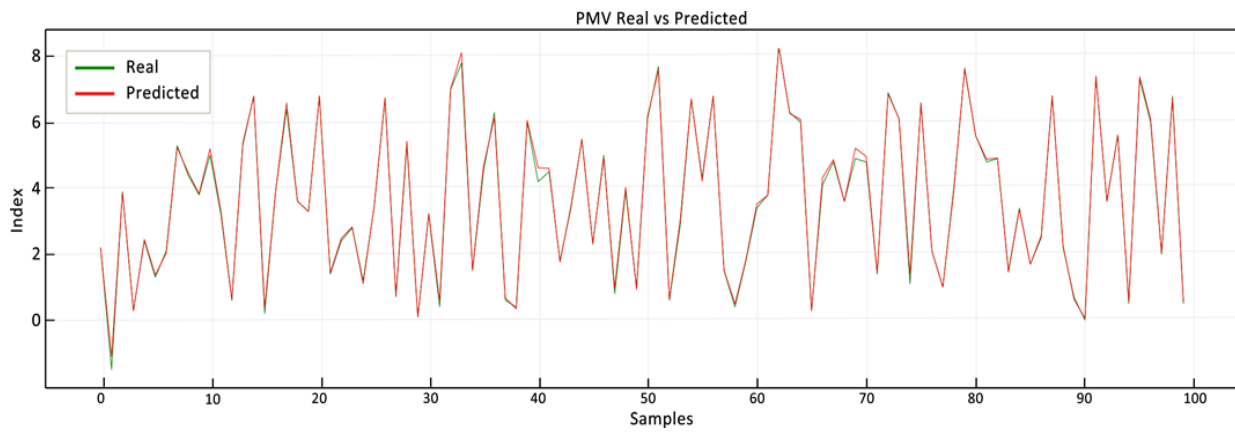
**Figure 3.1: Comparative Graph of Output (a) PET (b) PMV (c)  $T_{mrt}$  of Testing Samples from Applied Models.**

## Annex

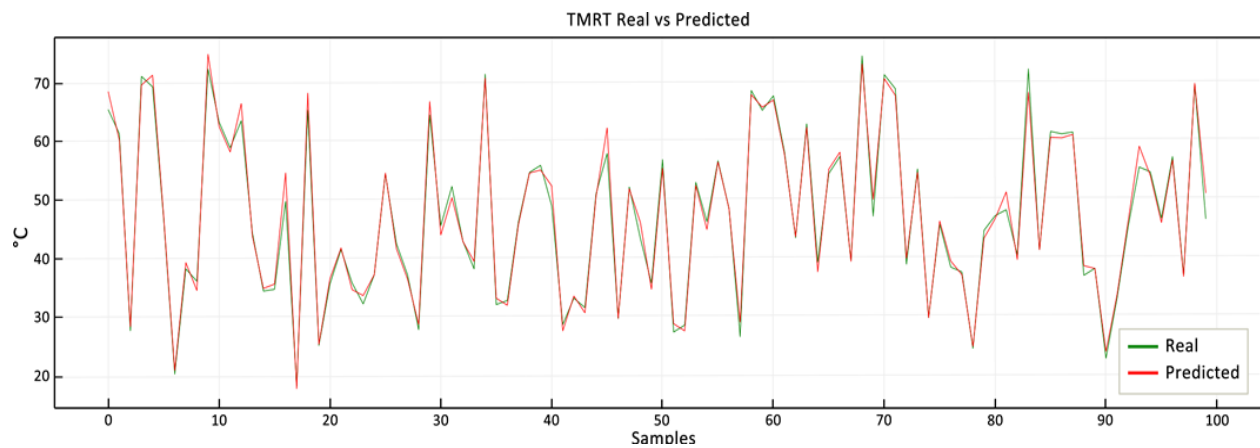
The GRU model was suitable with higher accuracy in predicting heat stress with meteorological data. The model has been tested in two-phase for outputs ( $T_{mrt}$ , PMV, PET) once with the test data and once with the real data from the summer of 2021 to validate the model with the reference software. Graphs of two validation phases for GRU are shown in **Figures A3.1** and **A3.2**.



(a)

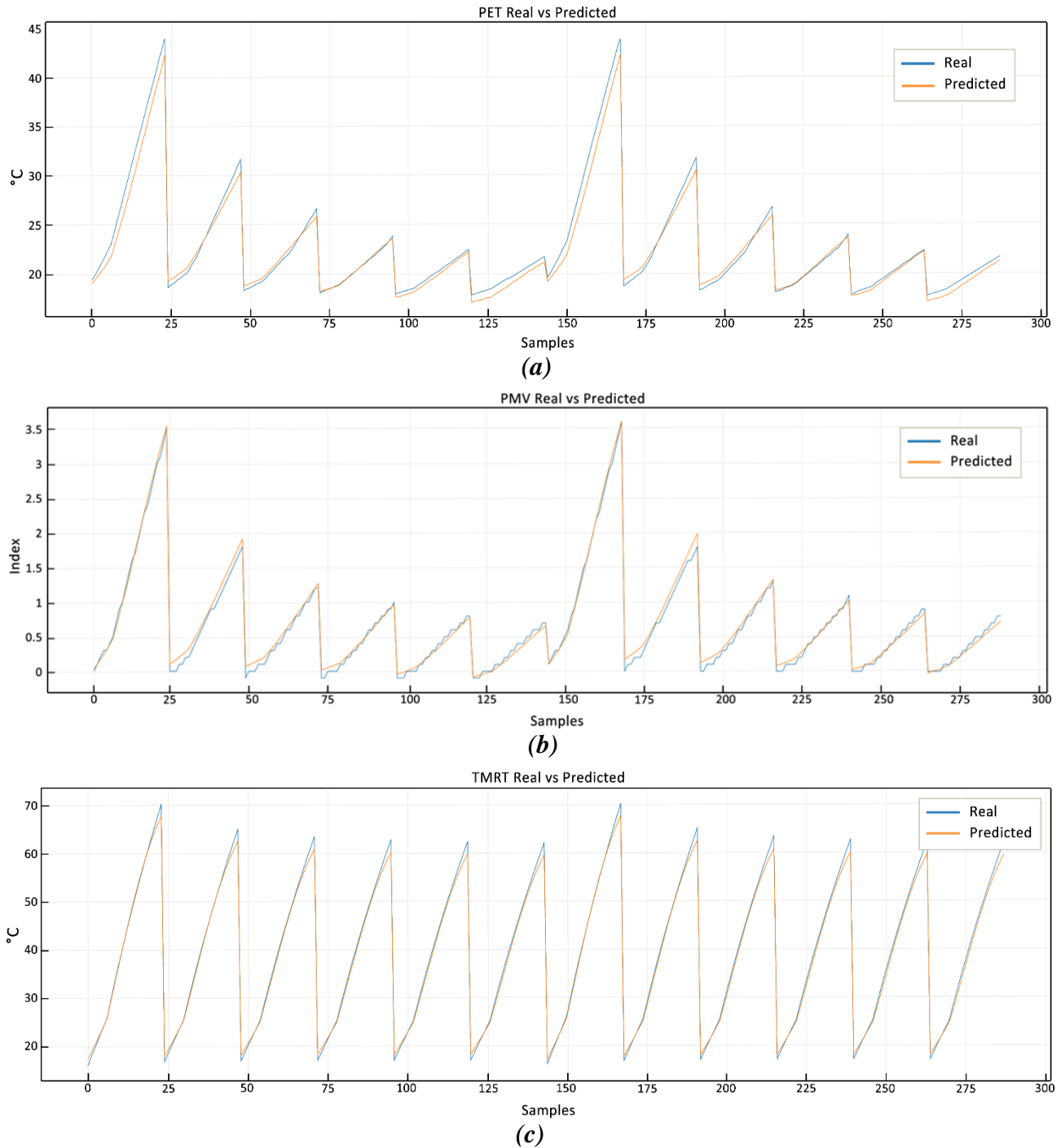


(b)



(c)

**Figure A3.1: Validation of Model Outputs Testing Phase 1 (a) PET (b) PMV (c)  $T_{mrt}$**



**Figure A3.2: Validation of Model Outputs Testing Phase 2 (a) PET (b) PMV (c)  $T_{mrt}$**

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## **Paper - II**

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# **Heat Stress Modeling Using Neural Networks Technique**

# HEAT STRESS MODELING USING NEURAL NETWORKS TECHNIQUE

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**Abstract:** Rising temperature especially in summer is currently a hot debate. Scientists around the world have raised concerns about Heat Stress Assessment (HSA). It depends on the urban geometry, building materials, greenery, environmental factor of the region, psychological and behavioral factors of the inhabitants. Effective and accurate heat stress forecasts are useful for managing thermal comfort in the area. A widely used technique is artificial intelligence (AI), especially neural networks, which can be trained on weather variables. In this study, the five most important meteorological parameters such as air temperature, global radiation, relative humidity, surface temperature and wind speed are considered for HSA. System dynamic approach and a new version of the Gated Recurrent Unit (GRU) method is used for the prediction of the mean radiant temperature, the mean predicted vote and the physiological equivalent temperature. GRU is a promising technology, the results with higher accuracy are obtained from this algorithm. The results obtained from the model are validated with the output of reference software named Rayman. Django's graphical user interface was created which allows users to select the range of thermal comfort scales based on their perception which depends on the age factor, local weather adaptability, and habit of tolerating the heat events. It also gives a warning to the user by color code about the level of discomfort which helps them to schedule and manage their outdoor activities. Future work consists of coupling this model with urban greenery factors to analyze the impact on the estimation of heat stress.

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**Keywords:** Artificial intelligence, thermal comfort, modeling, system dynamic approach and urban heat stress.

## 1. INTRODUCTION

In 2003, Europe experienced the driest and hottest summer since AD 1500, responsible for the death toll of 30,000 from the heat. Encountering this, team of scientists (Poumadere et al., 2005) suggested that this European heat wave could have occurred due to climate change. The increase in temperature worsens health problems. In addition, from a physiological point of view, during peak summers, when the temperature exceeds the normal tolerance limit of the human body which can lead to circulatory collapse or dehydration leading to death. It becomes unfavorable in a vulnerable population, comprising of children, old aged people, and handy-capped people (Luber and McGeehin, 2008).

Due to human activities, the properties of the local climate are altered (Kalnay and Cai, 2003). Urbanization around the world is happening at an accelerating rate, with global warming which is increasing Heat Stress (HS). It is imperative to identify certain factors that contribute to the intensification of HS (Fischer and Schär, 2010), (McDonald et al., 2011). In general, the external factors that influence the formation of Urban Heat Stress (UHS) are: seasons, synoptic conditions and climate. There are many researchers have worked hard to extract the influence of meteorological parameters on HS (Arnds et al., 2017, Hoffmann, 2012,

Hoffmann and Schlünzen, 2013 b, Ivajnsič and Žiberna, 2019).

Many parameters are considered while calculating HS in metropolitan cities (Akbari et al., 1990). The fundamentals of various numerical micro-scale models emphasize the synergy of urban fabric (land surface and building materials) and meteorological parameters; solar radiation (diffuse, direct), airflow and heat transfer from open surfaces (Grimmond, 2007). Air temperature ( $T_{air}$ ) is the most used input parameter, followed by mean radiant temperature ( $T_{mrt}$ ), after surface temperature ( $T_s$ ) has been applied, and rarely wind speed ( $W_s$ ) was used as an input parameter (Mirzaei, 2015). In 2019, a study on assessment of thermal comfort in open urban areas used the input factors; location, activity, gender, locality, age group, temperature of the globe,  $T_{air}$ , Solar Radiation (SR), Relative Humidity (RH),  $W_s$ , wind direction and the output was Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET),  $T_{mrt}$  and Standard Effective Temperature (SET) (Tsoka et al., 2018). In another study, an advanced algorithm based on neuro-fuzzy logic was attempted to create predictive models (Kicovic et al., 2019) and concluded that SR has the highest impact compared to  $T_{air}$  on thermal comfort of visitors in urban areas. In 2019, team of Kuala Lumpur University Campus worked on the Heat Stress Assessment (HSA). The



following meteorological data was used in their research as input variables:  $W_s$ , wind direction, initial atmospheric temperature, RH, cloud cover, location, soil data, building characteristics, walking speed, mechanical factor, heat transfer, clothing data to calculate  $T_{mrt}$ , PMV and PET values.  $T_{mrt}$  is the key meteorological parameter that affects the human energy balance, PMV and PET are significant indices, which are under the influence of  $T_{mrt}$  (Ghaffarianhoseini et al., 2019). In Previous studies urban geometry with green adaptive measures were missing during estimation of HS which is extremely difficult, mainly due to the complexity of the urban system. Artificial intelligence (AI) is a widely used technique to deal such problems. The support vector machine (SVM) is machine learning approach was used for the estimation of PMV. The results obtained with 76.7% accuracy which was twice as high as the widely adopted Fanger model which has an accuracy of 35% (Farhan et al., 2015). Recently, deep learning (DL) approaches have been reported with high precision results. Particularly, Convolutional and Long-Short Term Memory (LSTM). Recurrent Neural Networks (RNNs) have been used to predict hourly  $T_{air}$  with much less error (Hewage et al., 2021). In this study, a system dynamic approach is used for choosing the influenced variables of weather for HSA. The Rayman model (Matzarakis et al., 2007b, Matzarakis et al., 2010) is initially used for collection of simulated PET, PMV and  $T_{mrt}$  data and for comparative reference. The recurrent neural network (RNN) with memory function is used for modeling which is apparently more suited to this type of task. In this article, we make 3 contributions.

- We used Gated Recurrent Units (GRU) networks (Cho et al., 2014), which largely contributes to mitigating the problem of gradient vanishing of RNNs through the gating mechanism and simplify the structure while maintaining the effect of LSTM.
- High precision is achieved by the model and coupled with a friendly user interface that recognizes the individual thermal sensation level corresponding to the results.
- The database makes it possible to analyze the thermal comfort scales chosen by the users.
- The developed model is flexible, which will allow in the future to couple it with real data on the cooling effect of urban greenery and estimate the absolute HS for individuals. The remainder of this paper is organized as follows: the methodology is discussed in section 2, section 3 covers the model framework and experimental results. Section 4 presents framework of the GUI. Finally, conclusion in section 5.

## 2. METHODOLOGY

### 2.1 Systemic Dynamic Approach

As mentioned in the previous section that the mitigation of thermal discomfort caused by climate change is today's challenge; it happens due to a complex environment where multiple parameters are involved with their known behavioral feedback. To encounter this complex issue, a holistic dynamic systems approach is used which connects and emerge various influencing variables and address the nonlinear and linear interactions between them. This article proposes a systems dynamic modeling approach to simulate

HS in a complex environment using interdependent factors that are strongly influenced by UHS. The systematic approach of this study is presented in Fig.1.

Most often, there is an uncertainty about the responses and strengths of interactions in such model, but it is always contented to see conditions resulting in behaviors that are plausible and internally consistent. The systems approach allows user to compare a number of assumptions and alternative strategies and it makes the model simple to understand, without trivializing the underlying assumptions and interrelated processes.

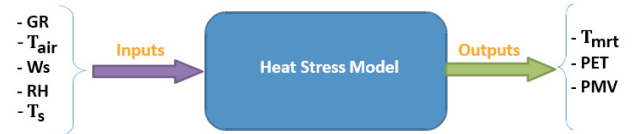


Fig.1 System dynamic approach for the assessment of heat stress

### 2.2 Data Generation

The Rayman model is beneficial for wave radiation flux densities in complex or simpler environments (Matzarakis et al., 2007 b). It is used throughout the simulation for data generation. Four variables such as GR, RH,  $T_{air}$  and  $W_s$  were considered as the main input variables for the calculation of PMV, PET and  $T_{mrt}$ . The calculated strategy consisted of varying a one variable for each simulation and it was repeated for every point to observe the variations of each input on the output.

### 2.3 Data Selection

The output data file is received with  $T_{mrt}$ , PMV, PET, thermal radiation (TR) and  $T_s$  corresponding to the main input variables. Later, the data was further analyzed by correlation coefficient against each output variable and evaluated the significant influential input variable affecting the behavior of the system Fig.2 shows the correlation of the most influenced input variables affecting the output variables (i.e., PMV, PET,  $T_{mrt}$ ). We included 5 important variables as inputs (X) with 3 outputs (Y) while the remaining variables found with low dependence were neglected.

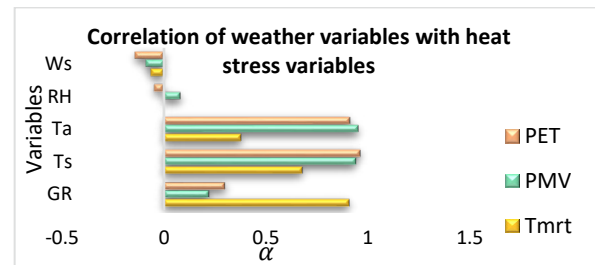


Fig.2 Correlation of weather variables with heat stress

## 3. MODELING FRAMEWORK

The final and stabilized model was produced in several stages. The frame work is shown in Fig.3 and each procedure

is discussed in the following subsections.

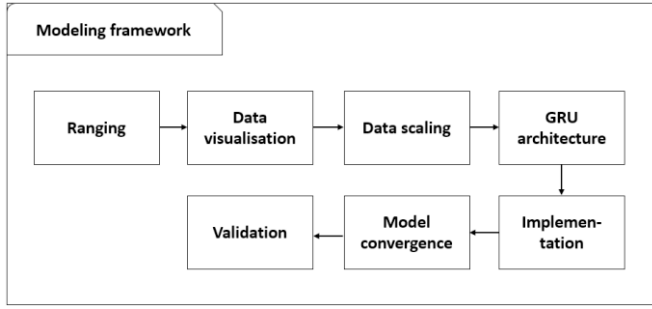


Fig.3 Modeling Framework

### 3.1 Data Ranging

Data ranging helps to determine the number of different classes present in the data and gives the basic idea of the certainty of output below the range of input limits. It also helps to understand the distribution and spreading range of the data by looking at the mean value, the standard deviation and percentile distribution for numeric values. Graphical presentation of the data ranging is shown in Fig.4.

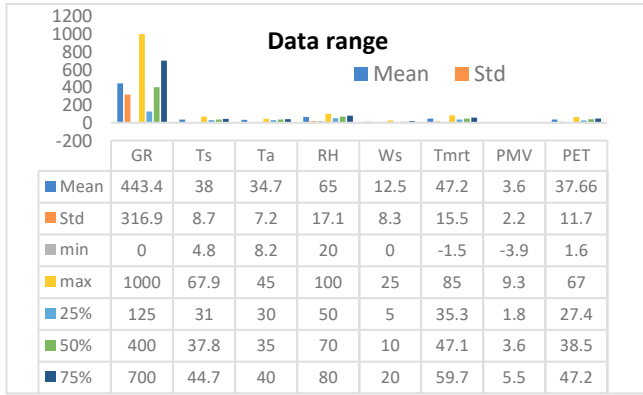


Fig.4 Graphical presentation of data ranging

### 3.2 Data Preparation

This step is necessary to understand the dataset to avoid estimation problems. The correlated attributes of the data are discussed in the section above. This is the fastest way to see if the features correspond to the output.

### 3.3 Probability Density Function

To visualize the likelihood of an outcome in a given range, we estimated a Probability Density Function (PDF) from the available data. First, we observed the density of a random variable  $x$  with a simple histogram and identified the probability distribution  $p(x)$ . The PDF is shown in Fig.5 (a) PET (b) PMV and (c)  $T_{mrt}$  discrete random variable and the probabilities ( $P(X) = x$ ) for all the possible values of  $x$ . The area below the curve indicates the interval in which the variable will fall and the total area of the interval is equal to the probability of occurrence of a single random variable.

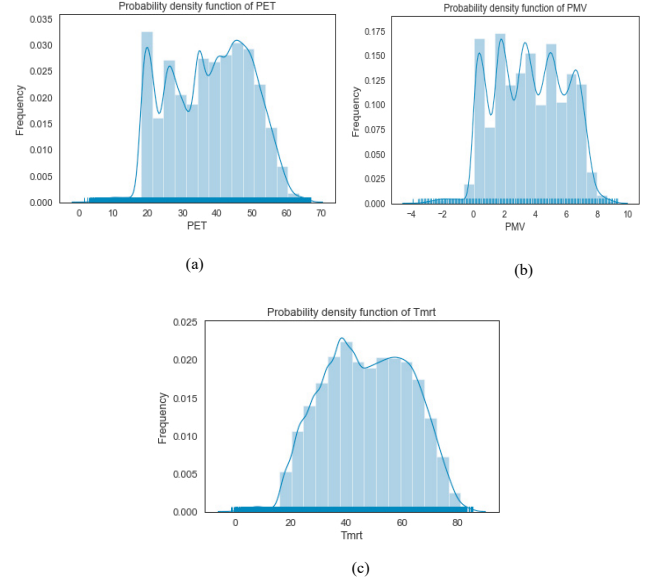


Fig.5 Probability distribution of (a) PET (b) PMV (c)  $T_{mrt}$

### 3.4 Resampling

Resampling the dataset is necessary to generate confidence intervals, it helps to quantify the uncertainty, to gather data and best use in the predictive problem. After visualizing the dataset using PDF, the hourly data is resampled over 30 minutes, but it was observed that sum of the resampled dataset have similar structures.

### 3.5 Data scaling

Scaling and normalization are important where numeric values transforms and data points can have specific useful properties. The difference is that in scaling, the data range is changed while when normalizing, the shape of the data distribution is changed. Min: max scaling and normalization is the simplest method to resize the range of characteristics in  $[0, 1]$ . It is found by using eq. (1)

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (1)$$

Sklearn library helps in making random partitions for both subsets for training data and for test data.  $X$  and  $Y$  arrays are divided into 4 more arrays, 70% of input and output data sets (73616, 5) (73616, 3) are trained for deep learning, 30% (31551, 5) (31551, 3) kept for testing phase to fully guarantee the randomness of each use of the data set.

### 3.6 The model architecture

For solving the vanishing gradient problem of a standard RNN, the GRU model uses update gate and reset gate. These are two vectors which decide what information should be passed and can be trained to retain information from the past, without washing it out over time. It removes information which is irrelevant for the prediction. The model is based on governing eq. (2-5). The structure of the GRU is shown in Fig.6.

Where;  $x_t$  is an input vector,  $(T_s, T_{air}, GR, RH$  and  $W_s)$   $h_t$  is an output vector  $(T_{mrt}, PMV, PET)$ ,  $h'_t$  is candidate activation vector,  $z_t$  is update gate vector,  $r_t$  is reset gate

vector,  $w_z$  and  $u_z$  are weight matrices it initializes to 0 or  $[-1, 1]$ ,  $b_n$  represents bias vectors with  $n \in r$ ,  $h$ ,  $\sigma_g$  is a sigmoid function:  $S(x) = \frac{1}{1+e^{-x}}$  and  $\phi_h$  is original is a hyperbolic tangent:  $\tanh x = \frac{\sinh x}{\cosh x} = \frac{e^x - e^{-x}}{e^x + e^{-x}} = \frac{e^{2x} - 1}{e^{2x} + 1}$

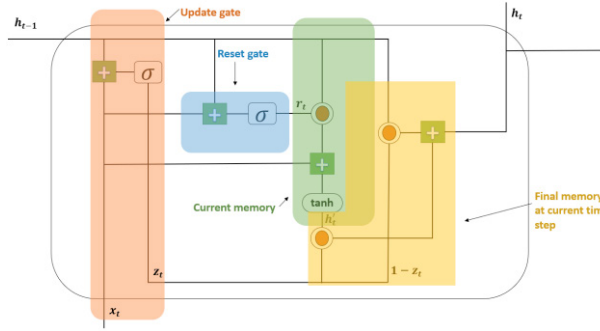


Fig.6 GRU Unit at time step t

We update the gate  $z$  for the time step  $t$  using eq. (2).

$$z_t = \sigma(w_z x_t + u_z h_{t-1} + b_z) \quad (2)$$

Vector  $x_t$  in matrix multiplied it with  $w_z$  and added with the multiplication of  $u_z$  and  $h_{t-1}$  (Note that  $h_{t-1}=0$ ), then we have added results with the bias  $b$ , afterwards the sigmoid function was activated.

The reset gate is used, which helps to decide how much of the past information is needed to forget with the help of eq.(3)

$$r_t = \sigma(w_r x_t + u_r h_{t-1} + b_r) \quad (3)$$

This is the same as update gate, the difference comes from the weights and the usage of the gates, so these are two different vectors  $r_t$  and  $z_t$ . It is noticed that how exactly the gates affect the final output. It is started with the use of the reset gate and introduces a new memory content by using  $\tanh$  which creates a new memory vector and store the relevant information from the past using eq. (4).

$$h'_t = \phi(w_h x_t + u_h (r_t \odot h_{t-1}) + b_h) \quad (4)$$

In the last step, the network calculates the current hidden state output vector  $h_t$  which holds information for the current unit and passes it down to the network. In order to do this, the update gate is required. It determines what to collect from the current memory content  $h'_t$  and what from the previous steps  $h_{t-1}$ . This is the final output calculated by using eq. (5).

$$h_t = (1 - z_t) \odot h_{t-1} + z_t \odot h'_t \quad (5)$$

### 3.7 Model convergence

The mean Square Error (MSE) loss function and the efficient Adam version of stochastic gradient descent is used to measure the accuracy and optimize the deep learning model. Adam optimization is a stochastic gradient descent method that is based on adaptive estimation of first and second order moments. It is the best among the adaptive optimizers with perfect adaptive learning rate. MSE is calculated by eq. (6). where  $n$  is the total amount of the dataset,  $Y_i$  is the real observed  $\hat{Y}_i$  is the estimated data.

$$MSE = \frac{1}{n} \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 \quad (6)$$

$$RMSE = \sqrt{MSE}$$

The GRU network is implemented using the tensor flow deep learning package. Hereby, we provide a detailed description of our GRU based models as follows:

- The first visible input layer consists of 128 GRU cells, and the dropout rate is 0.5 with the relu activation function.
- Second hidden dense layer consists of 256 neurons with 3 outputs where the dropout rate is 0.25 and linear activation function sets for the last layer.
- Finally, the Adam optimization algorithm is used for network training. We set the patience of the training process over 40 epochs with a batch size of 256, can be seen in Fig.7.
- 70% of the data was used for learning and 30% of data in the dataset was employed as test data which is later used for the validation. An accuracy score of 99.36% is obtained with MSE= 0.0002.

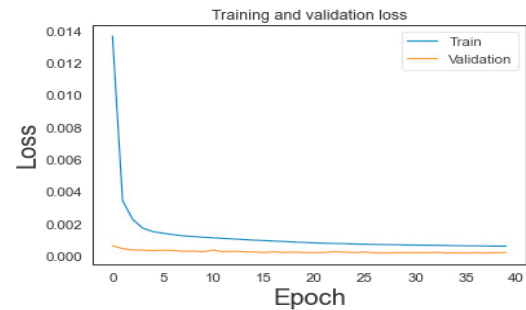


Fig.7 Graph of iterations performed for training and validation

### 3.8 Model implementation

Based on the systems approach of this model, GR, RH,  $T_{air}$ ,  $W_s$  and  $T_s$  forms the input vector  $x_t$ , where  $x_t$  is represented as follows:  $[x_{t1} : GR; x_{t2} : T_s; x_{t3} : T_{air}; x_{t4} : RH; x_{t5} : W_s]$

Each row of the input matrix  $x_t$  is taken into the GRU unit and the obtained output ( $h_t$ ) vectors are represented as follows:  $[h_{t1} : T_{mrt}; h_{t2} : PMV; h_{t3} : PET]$  respectively. Eq. (7-9) are used for predictions derived from governing eq. (2-5) of GRU model.

$$\begin{pmatrix} z_t \\ r_t \end{pmatrix} = \begin{pmatrix} \sigma \\ \sigma \end{pmatrix} \cdot \begin{bmatrix} w_z & u_z \\ w_r & u_r \end{bmatrix} \times \begin{pmatrix} x_t \\ h_{t-1} \end{pmatrix} + \begin{pmatrix} b_z \\ b_r \end{pmatrix} \quad (7)$$

$$h'_t = \tanh_x [w_h \ u_h] \times \begin{pmatrix} x_t \\ r_t \odot h_{t-1} \end{pmatrix} + b_h \quad (8a)$$

$$h'_t = \left( \frac{e^{2x}-1}{e^{2x}+1} \right) \cdot [w_h \ u_h] \times \begin{pmatrix} x_t \\ r_t \odot h_{t-1} \end{pmatrix} + b_h \quad (8b)$$

$$h_t = z_t \odot h'_t + (1 - z_t) \odot h_{t-1} \quad (9)$$

$h_t$  is initialized from 0 so,  $h_{t-1} = 0$ , but at  $t=1$ ,  $h_t$  changes and the weight matrices ( $w$ ,  $u$ ) of the input and output data of the previous cells updated by using eq. (10) [where  $\alpha$  is

adjusting parameter which is  $>0$ ] and  $error_t$  = error at time step  $t$  and learning rate controls the model in response to the estimated error each time to update the model weights.

$$W_{t+1} = W_t + error_t * learning\ rate * \alpha \quad (10)$$

### 3.9 Validation

The performance of the developed deep learning models was validated using the test data. This process was independent of the learning process of the algorithm. Validation process repeated twice. First, the input variables of 100 test samples from the test dataset. The resulting output (PET) of the model is plotted with the actual output of the dataset can be seen in Fig.8. To check the reliability of the model, another dataset with realistic summer measurements is used and plotted 300 examples (see Fig.9). We notice that the model responds efficiently and reliable results are obtained which are compared to the reference software.

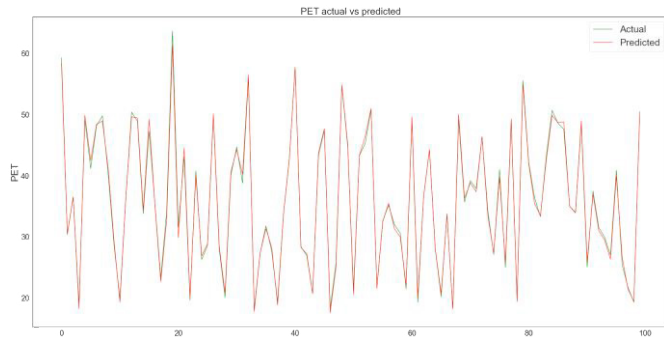


Fig.8 Validation of model outputs testing phase 1 for PET.

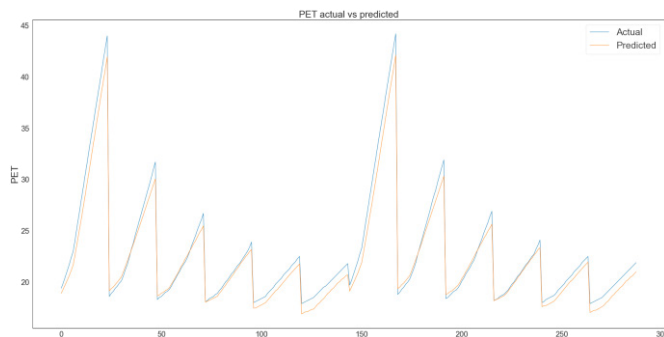


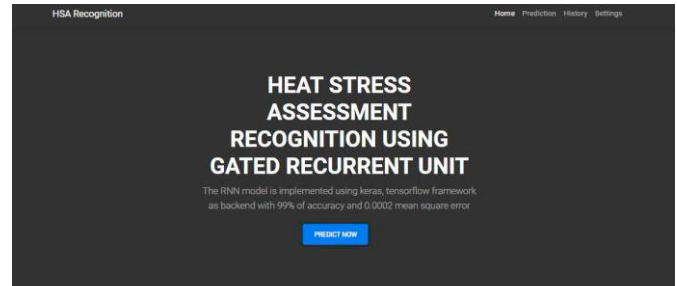
Fig.9 Validation of model outputs testing phase 2 for PET.

## 4. WEB BASED SIMULATION TOOL

After validation of the model, the open-source web framework based on Python, "Django" is used to develop the graphical user interface (GUI) for the evaluation of HS. This interface provides the platform for users to choose their thermal comfort scale based on their current feeling and considering the obtained assessment results plan outdoor activities. The interface also provides a platform where the users can compare their current comfort level with the given index results, which can help them compare their results and choose the index that matches with the situation. For example, it is shown in Fig.10d that PET and PMV results indicate the different comfort zones which may needs the

user's assessment. The functions and use of the GUI are as follows:

- Home page (Fig.10a): It gives general information on thermal stress.
- Parameters (Fig.10b): Here users can either set the thermal comfort scale for PET according to their thermal perception or choose the standard default parameters and save them. Users can do the same for PMV and  $T_{mrt}$ .
- Predictions (Fig.10c): The input variables are necessary for the prediction.
- History (Fig.10d): It records entries and results calculated by random users.



#### Mean Radiant Temperature

The mean radiant temperature (MRT) is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure.



#### Physiological Equivalent Temperature

PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed.



#### Predicted Mean Vote

The predicted mean vote (PMV) was developed by Poul Ole Fanger at Kansas State University and the Technical University of Denmark as an empirical fit to the human sensation of thermal comfort. It was later adopted as an ISO standard.

(a)

(b)

(c)



## History

#	Global radiation (W/m <sup>2</sup> )	Surface temperature (°C)	Air temperature (°C)	Relative Humidity (%)	Wind speed (m/s)	Tmrt (°C)	PMV	PET (°C)
1	600	45.4	45	40	1	61.65	5.97	51.27
2	363	28	25	65	3.4	36.32	0.84	23.60

(d)

Fig.10 Pictorial View of GUI

## 5. CONCLUSION

In this study, system dynamic approach and GRU network is used as a powerful method to predict HS. The variables which strongly effects the system are analyzed and extracted as input variables ( $T_{air}$ ,  $T_s$ , GR, RH,  $W_s$ ). The GRU network is modeled, after using the grid search to find the optimal hyper-parameters and estimates the outputs ( $T_{mrt}$ , PET, PMV). For the given dataset, the proposed GRU training algorithm was 99.36% accurate. The model was coupled with GUI for individual HSA. This study concludes that system approach helps to assess HS even in the complex environment and address the nonlinear interactions of the variables. Also, a user can use this interface for their own comfort definition which will give the platform to analyze the different thermal comfort scale chosen by users. There are still some limitations in this study that requires further research. An optimization and extension in the model may be future work. It will be coupled with the cooling effect of urban greenery which may influence the estimation of HS.

## ACKNOWLEDGEMENT

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# Chapter – 4

## Heat Vulnerability Analysis and Field Monitoring in Amiens

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This chapter is a case study of a medium-sized French city named Amiens. It consists of the following two parts:

- ❖ Part–A is intended for estimating the current heat vulnerability index considering influential parameters and data from recent years.
- ❖ Part–B is based on field measurements to calculate the cooling effect of tree species. Measurements have been taken in 3 public spaces in the city centre

## Part - A

# Heat Vulnerability Index Mapping: A Case Study of a Medium-Sized City (Amiens)

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The **part–A** of this chapter has been published as “Heat Vulnerability Index Mapping: A Case Study of a Medium-Sized City (Amiens)” on “Climate” This paper is attached at *Paper - III* with kind permission from the journal and can be cited as:

*Qureshi AM, Rachid A. Heat Vulnerability Index Mapping: A Case Study of a Medium-Sized City (Amiens). Climate. 2022; 10(8):113. <https://doi.org/10.3390/cli10080113>*

**Keywords:** Heat vulnerability index; heat mapping; heat illness; remote sensing; GIS

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### Major Findings

In this study, real weather, and air quality monitoring data from a medium-sized city in Hauts de France (Amiens) was analysed. It is noticed that extreme events (heat and poor air quality) are interdependent and recorded at the same time in summer season. The high correlation was calculated between the heat stress hours and poor air quality events especially with ground level ozone (0.8). The Heat Vulnerability Index (HVI) in Amiens for extreme heat days recorded over three years (2018-2020) was estimated using the Principal Component Analysis (PCA) technique. Risk factors that play an important role in HVI such as (a) socioeconomic and demographic data, (b) air pollution, (c) land use and cover, (d) heat-related illnesses of the elderly, (e) social vulnerability and (f) remote sensing data (Land surface temperature (LST), mean elevation, normalized difference vegetation index (NDVI) and normalized difference water index (NDWI)) were considered. High HVI has been found to exist in three typical areas: (1) areas with dense population and low vegetation, (2) areas with artificial surfaces (built-up areas), and (3) industrial areas. Low HVI areas are found in natural landscapes such as rivers and grasslands. The derived HVI can assist decision-makers and urban planners for intervening heat resilience measures at hot spots and highlights the zones which are at high risk for future heat events.

## **Paper - III**

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### **Heat Vulnerability Index Mapping: A Case Study of a Medium-Sized City (Amiens)**



## Article

# Heat Vulnerability Index Mapping: A Case Study of a Medium-Sized City (Amiens)

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**Abstract:** Urbanization, anthropogenic activities, and social determinants such as poverty and literacy rate greatly contribute to heat-related mortalities. The 2003 strong heat wave (Lucifer) in France resulted in catastrophic health consequences in the region that may be attributed to urbanization and other anthropogenic activities. Amiens is a medium-sized French city, where the average temperature has increased since the year 2000. In this study, we evaluated the Heat Vulnerability Index (HVI) in Amiens for extreme heat days recorded during three years (2018–2020). We used the principal component analysis (PCA) technique for fine-scale vulnerability mapping. The main types of considered data included (a) socioeconomic and demographic data, (b) air pollution, (c) land use and cover, (d) elderly heat illness, (e) social vulnerability, and (f) remote sensing data (land surface temperature (LST), mean elevation, normalized difference vegetation index (NDVI), and normalized difference water index (NDWI)). The output maps identified the hot zones through comprehensive GIS analysis. The resultant maps showed that high HVI exists in three typical areas: (1) areas with dense population and low vegetation, (2) areas with artificial surfaces (built-up areas), and (3) industrial zones. Low-HVI areas are in natural landscapes such as rivers and grasslands. Our analysis can be implemented in other cities to highlight areas at high risk of extreme heat and air pollution.



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**Keywords:** Heat Vulnerability Index; heat mapping; heat illness; remote sensing; GIS

## 1. Introduction

Climate change has greatly impacted the global mean temperatures and has resulted in strong heat waves during the last couple of decades. It has been responsible for heat-related morbidities and mortalities globally, including heat waves in the Balkans (2007), the Midwestern United States (1980), France (2003), and Russia (2010) [1,2]. In August 2003, France was hit by a strong heat wave named Lucifer, with catastrophic health consequences. Heat events, as well as socioeconomic vulnerability, led to more than 14,800 mortalities in France due to dehydration, hyperthermia, and heat stroke [3]. Heat waves with urban heat islands can increase the death ratio, particularly for vulnerable people such as outdoor workers and elders who are socially isolated and/or with pre-existing disease [4,5]. Other influencing factors include urbanization, poverty, literacy rate, and possibly air pollution [6,7]. According to the World Health Organization (WHO), a 2 °C increase in the apparent temperature (AT) is a limiting warning that can prevent rising heat mortalities, but later studies proved that heat events are inevitable even if the global heat stress warning is restricted to 2 °C AT [8]. Mortality risk in France can be increased by 1–1.9 log for every 1 °C AT. Long heat waves (more than 5 days) have an impact of 1.5–5 times greater than shorter events [9]. Urbanization promotes anthropogenic activities which lead to heat events. Adaptive strategies are necessary to protect the residents from heat-related events and health risks in the coming years.

Amiens is a medium-sized city in northern France, crossed by the Somme River. The hot season lasts 3 months, from June to August, where maximum air temperatures can

reach 41 °C [10]. The hottest month of the year in Amiens is July. It has been reported that the mean annual air temperature between 2000 and 2018 increased by 1 °C above the 20th century average, with 2003, 2011, 2014, 2017, and 2018 being the warmest years [11]. This threat of extreme heat events is likely to increase due to the combined effects of global warming and rapid urbanization in the future. Although the data related to the strong 2003 heat wave and associated adverse health outcomes have been evaluated previously [12], the Heat Vulnerability Index (HVI) was recently investigated for big cities, e.g., Camden, Philadelphia [13], London [14], and Sydney [15], where the influence of air quality was not considered except for the study presented by Sabrin for Camden [16]. To our best knowledge, there are no studies addressing the impact of heat waves on a medium-sized city using the HVI approach, where the population is less than one million. Within this context, the current study aimed to identify the heat-vulnerable communities and areas in Amiens where heat stress mitigation strategies are required. The main data types which we used for this study to develop the HVI model were (a) socioeconomic and demographic data, (b) air pollution, (c) land use and land cover, (d) elderly heat illness, (e) social vulnerability, and (f) satellite data (land surface temperature and mean elevation).

Heat maps of high spatial and temporal resolution are generated from satellite data, and HVI maps are derived using principal component analysis (PCA) to help urban planners and public health professionals to identify places at high risk of extreme heat and air pollution. This case study aims to bring attention to the fact that medium-size cities are also vulnerable to heat, requiring some proactive measures against future extreme heat events. Our suggested index can be a useful tool in decision making for dealing with extreme events and can guide city planners and municipalities.

The paper is organized as follows: the methodology is presented in Section 2 with data analysis and the developed working model. It also provides the information of the used technique and the influence of components. The obtained results and HVI map with valuable information are given in Sections 3 and 4, respectively. The paper ends with a conclusion in Section 5, with some perspectives and recommendations in Section 6.

## 2. Materials and Methods

Several parameters have been studied that have a possible correlation with extreme heat events and air pollution in urban settings, which were identified and discussed in the previous literature to develop our conceptual model [14,17]. The methodology for the case study was developed as a working model for HVI mapping, as shown in Figure 1. In this study, risk factors such as social vulnerability (factors taken from the literature) and the environment (identified after extreme event analysis of the studied area) are discussed in this section.

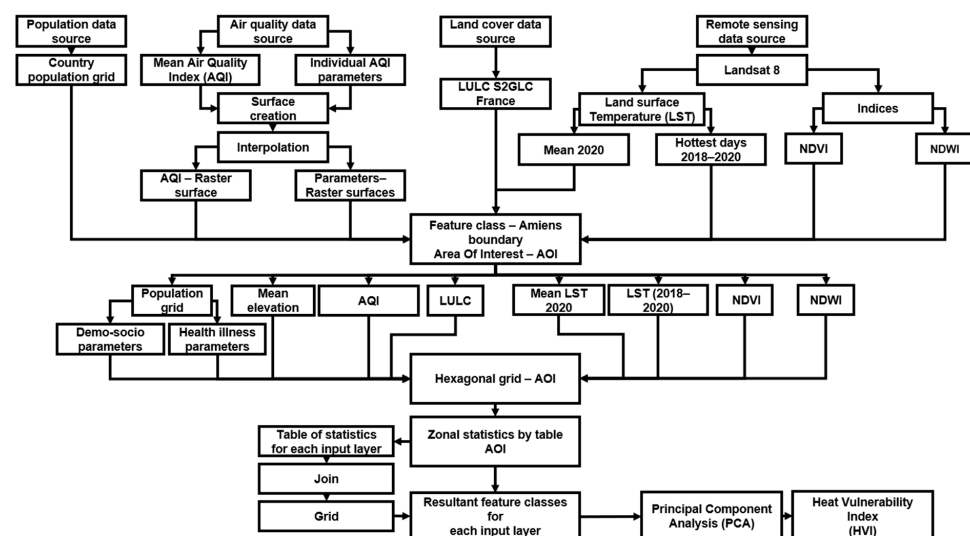


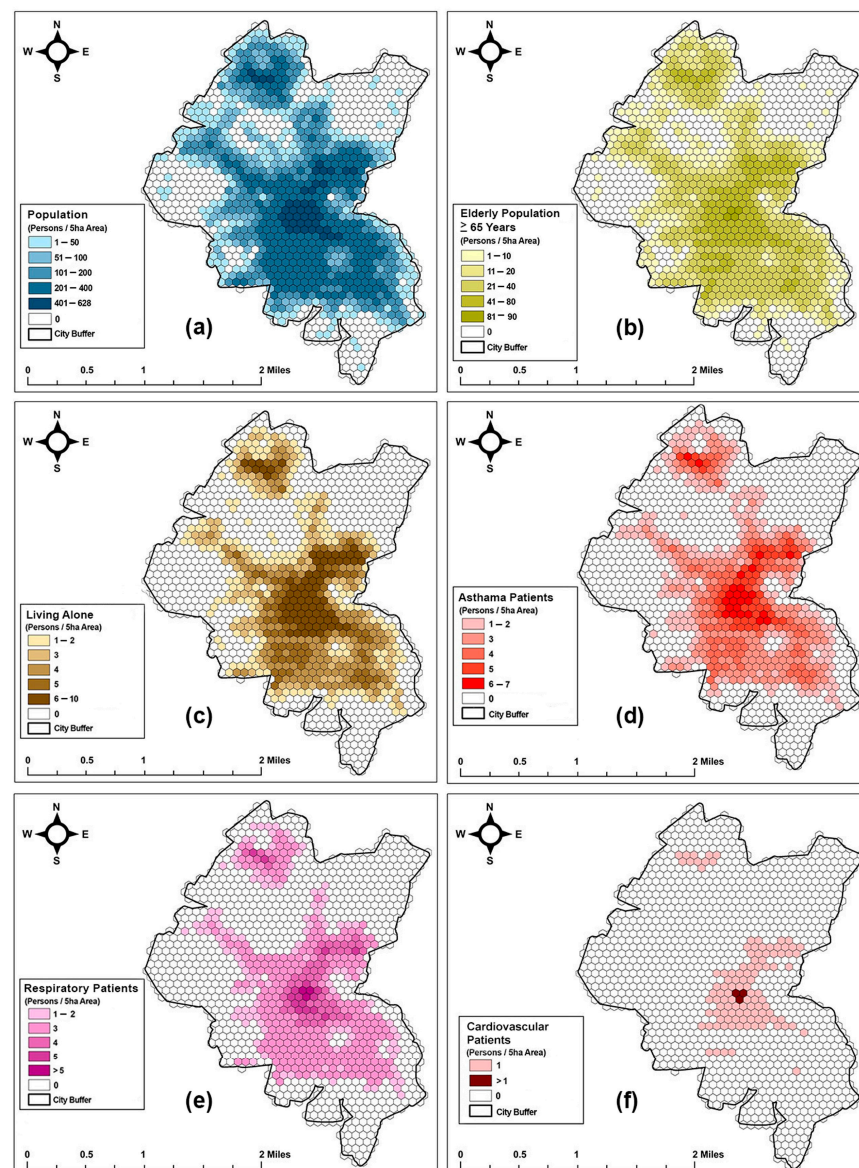
Figure 1. Working model for Heat Vulnerability Index mapping of Amiens.

## 2.1. Identification of Risk Factors

### 2.1.1. Social Vulnerability Factors (SVF)

Age, pre-existing medical conditions, and social deprivation are among the various key factors that make people likely to experience more adverse health outcomes related to extreme temperatures. References were used for the population density, poverty rate, illiteracy rate, vulnerable age group, illness rate (asthma, cardiovascular disease, and respiratory disease other than asthma), and isolated elderly (living alone in the summer), as presented in Table 1.

Mapping for the socially vulnerable population was performed using a dataset from world pop [18], which provides a population at a map scale of 100 m. Hexagon grids of 5 ha were generated in the area of Amiens city. Zonal statistics was used to extract the population at the grid level to maintain homogeneity of analysis throughout the study. In addition, a multi-frame population map of a specific group was also created, as presented in Figure 2.



**Figure 2.** (a) Total population in the city; (b) elderly population  $\geq 65$  years; (c) those living alone; (d) asthma patients; (e) patients with other respiratory diseases; (f) cardiovascular patients.



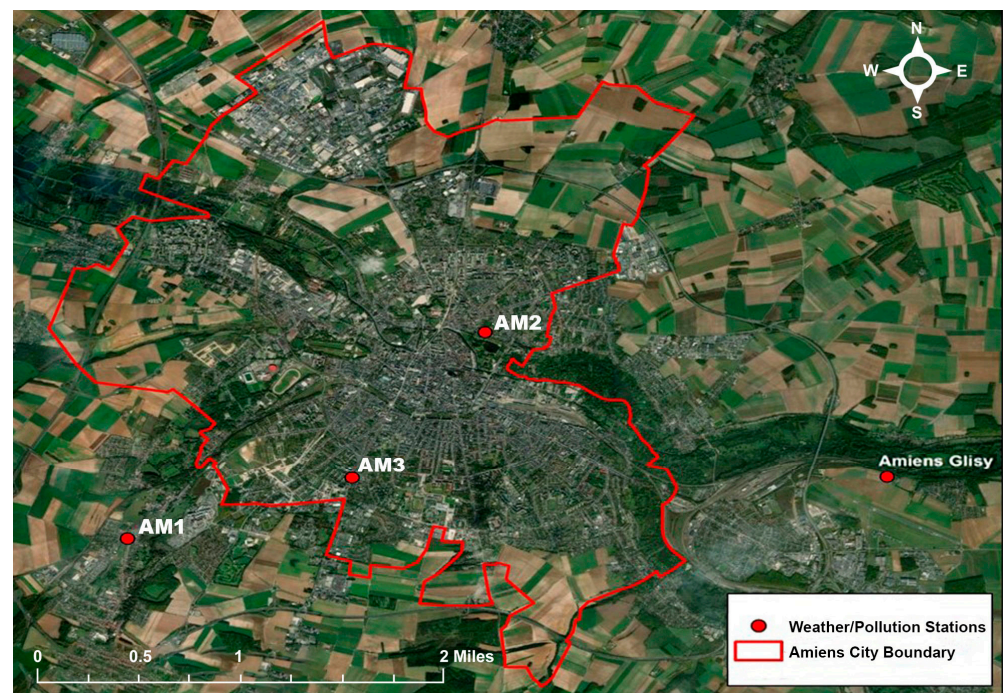
**Table 1.** Estimation of social vulnerability factors

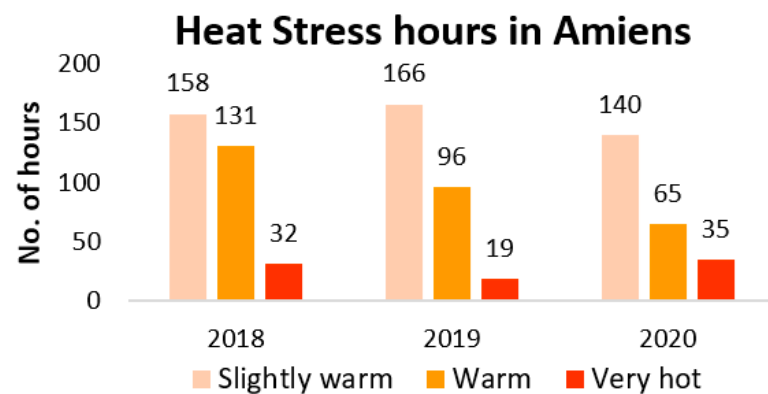
Factors	Estimated Statistics	Year	Source	Reference
<b>Poverty rate</b>	15% (17,045 habitants)	2020	French Newspaper “Courrier Picard” 2020	-
Elderly population >65	19% (25,246)	2014	National Institute of Statistics in France—INSEE	[19]
Illiteracy rate (no diploma aged >15 years)	22%	2015	Municipality of Amiens City population	[20]
Illness ratio of the elderly population	28 out of every 200 patients	2000	Insurance company survey	[21]
Cardiovascular patients	799 Elder = 112	2008	Research paper	[22]
Asthma patients	8% Total = (10,629) Elders = 1400	2014	Eurostat	[23,24]
Other respiratory diseases excluding asthma	6% Total = 7972 Elders = 1100			
Socially vulnerable elders in the summer	2000	2014	Article: “The city of Amiens watches over our seniors”	[25]

Note: The statistical data from referenced sources give the rough estimation of social vulnerability.

### 2.1.2. Extreme Event Analysis

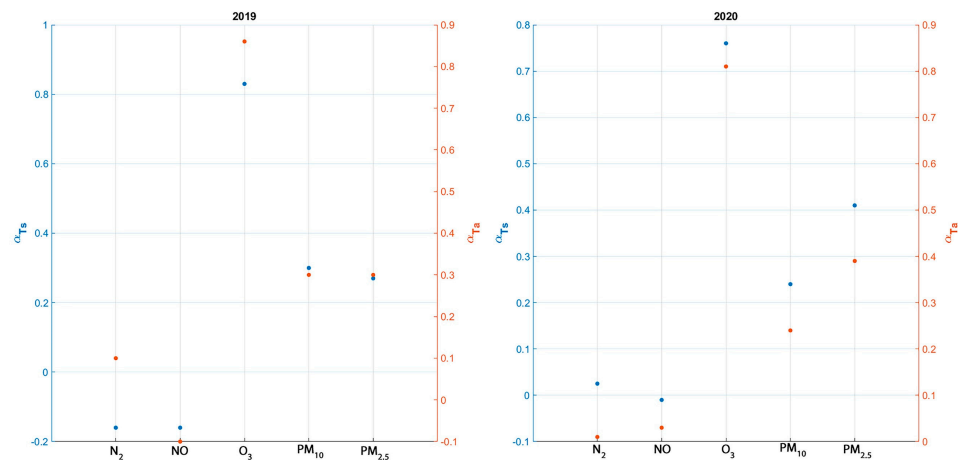
To identify the extreme events recorded, the hourly data for the summer (July and August) were collected from Météo France [10] and Atmo France [26]. Data were analyzed by dividing them into categories to estimate risk alerts. The Météo France weather station is located in Amiens Glisy, 14 km from the city center. Three air pollution stations are located in different areas (details for data recording are given in Table A1). The geographical locations of air pollution and weather stations can be seen in Figure 3. Weather data were analyzed to assess the levels and duration of heat episodes. The assumption scale was made by categorizing air temperature ranges into risk warnings: slightly warm (26–30 °C), warm (31–36 °C), and very hot (37–41 °C). This approach made it possible to analyze the huge hourly data during the summer seasons of 2018–2020. The number of hours of heat stress with their levels is presented in Figure 4.

**Figure 3.** The geographical locations of air pollution and weather stations.



**Figure 4.** Heat stress hours in Amiens (data source: Météo France).

The air quality data were obtained over the past 10 years from local monitoring stations referred to as AM1, AM2, and AM3, where certain non-regularization of monitoring was noticed, particularly in the AM3 station (details are provided in Table A1). The temperature (ambient and surface) and air quality data were analyzed for a correlation study from 2018 to 2020, and it was observed that, due to the irregularity, the air quality data of 2018 were not sufficient. However, data from 2019 and 2020 were adequate for this study. The correlation coefficients are plotted in Figure 5, showing that anthropogenic activities also increased the frequency and intensity of extreme heat. Moreover, a significant relationship was observed between heat events and ground-level ozone, representing the motivation of this research.



**Figure 5.** Correlation coefficient ( $\alpha$ ) of monitored air temperature ( $T_a$ ) and surface temperature ( $T_s$ ) with air pollutants during summer season (July and August) of 2019 and 2020 (data source: ATMO France).

### 2.1.3. Environmental Risk Factors

After analyzing the collected data, it was found that low air quality and an increase in temperature are risk factors that depend on urban geometry, the proportion of urban greenery, and materials. In current study, three main environmental risk factors are considered and mapped for the identification of heat-vulnerable areas. Further details are provided in the subsections below.

#### a. LST mapping of extreme heat days

Data for environmental risk factors such as land surface temperature (LST), normalized difference vegetation index (NDVI), and normalized difference water index (NDWI) were first collected in the area of study to create vulnerability maps. The city suffers from a lack of canopy-scale temperature readings, air quality data, and consistent weather stations,

which limited us to studying the spatial patterns of temperature and pollution in the city at high resolution. We only had data from one meteorological station, which was insufficient to achieve realistic and reliable data for spatial distribution. The city mainly relies on weather stations located outside the city for weather forecasts. Thus, temperature data were collected at fine spatial scales via the Landsat 8 earth observation satellite [27], which integrates the role of the built environment. Satellite data can be used to derive the surface temperature using high-spatial-resolution imagery and remote sensing techniques to study the effect of heat over a large area. Therefore, we used Landsat 8 multispectral satellite images to obtain high-resolution LST, NDVI, and NDWI data using Equations (1–4). The mean LST values at the pixel level show that Amiens experienced high LST on 27 July 2018, 25 July 2019, and 31 July 2020. Landsat 8 images were used to derive the LST raster layers. The maps appear to show regions with higher temperatures between 20 °C and 41.5 °C. The summer 2020 (July and August) mean LST map was also derived because last year is considered highly reliable for expected coming heat events. The derived maps are presented in Figure 6.

$$LST = \frac{T_{\text{sensor}}}{1 + (\lambda \times (T_{\text{sensor}} / \beta)) \ln(\epsilon)} \quad (1)$$

where LST is the land surface temperature, and  $T_{\text{sensor}}$  is the band 10 brightness temperature in K, later converted into °C [28],  $\lambda$  is the wavelength of the emitted radiance in meters,  $\beta = 1.438 \times 10^{-2}$  Mk, and  $\epsilon$  is the surface emissivity [29].

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \quad (2)$$

$$NDWI = \frac{G - NIR}{G + NIR} \quad (3)$$

where NIR is the near-infrared waveband (band 5 for Landsat 8), RED channels of remotely sensed images are the reflectance of the visible red waveband (band 4 for Landsat 8), and G represents the green channels.

For  $\epsilon$ , it is necessary to correct the spectral emissivity using the NDVI value.

$$\epsilon = 1 + 0.047 \ln(NDVI), \quad 0 \leq NDVI < 0.15 \quad (4)$$

In previous studies [30], mean elevation was taken as an indicator of PCA. In this study, altitude was considered an important factor in temperature distribution. The elevation was taken from the Shuttle Radar Topography Mission (SRTM) 30 m pixel raster data. This elevation of the terrain was used to visualize and analyze the flat or mountainous distribution areas.

#### b. Land use and land cover (LULC)

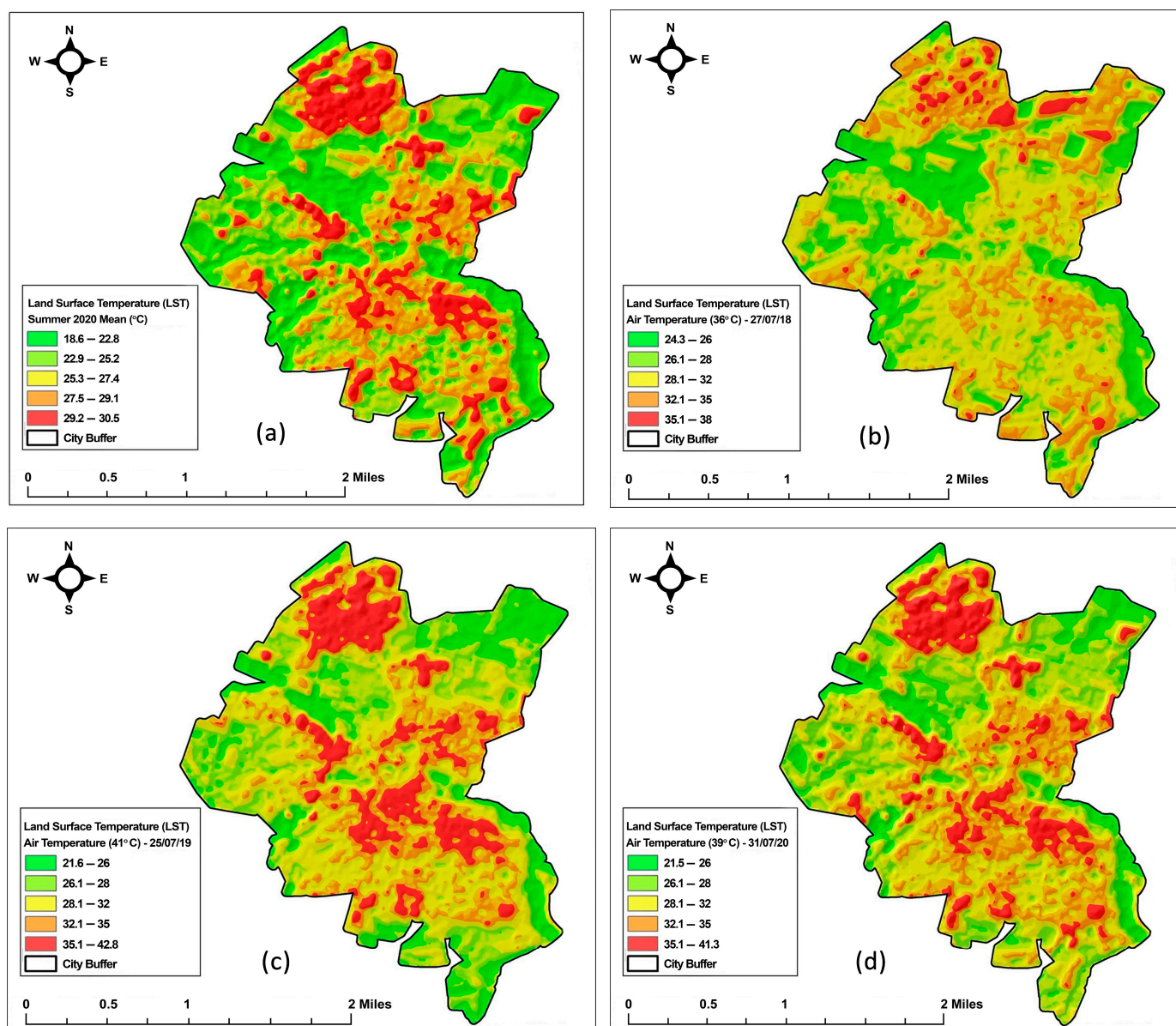
It can be observed that a large scattered hot area existed in the center of the city. The high LST was mainly distributed in the built-up areas of Amiens. These areas were combined with a land use/land cover map (Figure 7), and it was recognized that the high LST was mostly distributed in the following areas: (i) densely populated areas, (ii) areas with low vegetation coverage, (iii) areas with artificial surfaces, and (iv) industrial zones.

However, low-LST areas were mainly located in natural landscapes, such as rivers and grasslands. The LULC ratio of Amiens is shown in Table 2.

#### c. Air quality

The Air Quality Index (AQI) for 2019 and 2020 for the summer season (July–August) was estimated using the AQI calculator [31]. The inverse distance weighted (IDW) interpolation method was used to create the AQI surface to develop the maps in Figure 8. Additional layers of each raw pollution variable were also created, which were later used in the PCA for HVI calculations.





**Figure 6.** Land surface temperature maps: (a) summer mean 2020; (b) 27 July 2018; (c) 25 July 2019; (d) 31 July 2020. Note: The summer mean temperature is the mean LST of July and August 2020.

**Table 2.** LULC of Amiens.

S.No.	Class	Area (%)	Category for PCA	Total Area (%)
1	Artificial surfaces	31.65	Built-up area	31.65
2	Coniferous tree cover	1.17	Vegetation	56.88
3	Cultivated areas	26.69		
4	Deciduous tree cover	9.29		
5	Herbaceous vegetation	3.93		
6	Moors and heathland	15.80		
7	Natural material surfaces	1.99	Open areas	1.99
8	Marshes	4.68	Wetlands	2.22
9	Peatbogs	2.54		
10	Water bodies	2.26	Water	2.26
Total		100		100

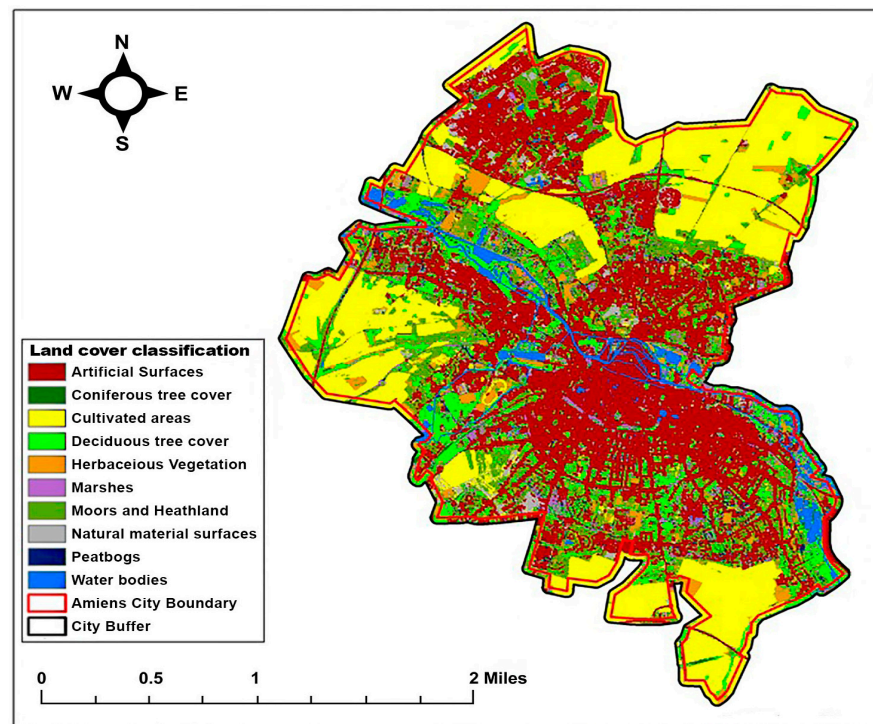


Figure 7. Land use/land cover map of Amiens.

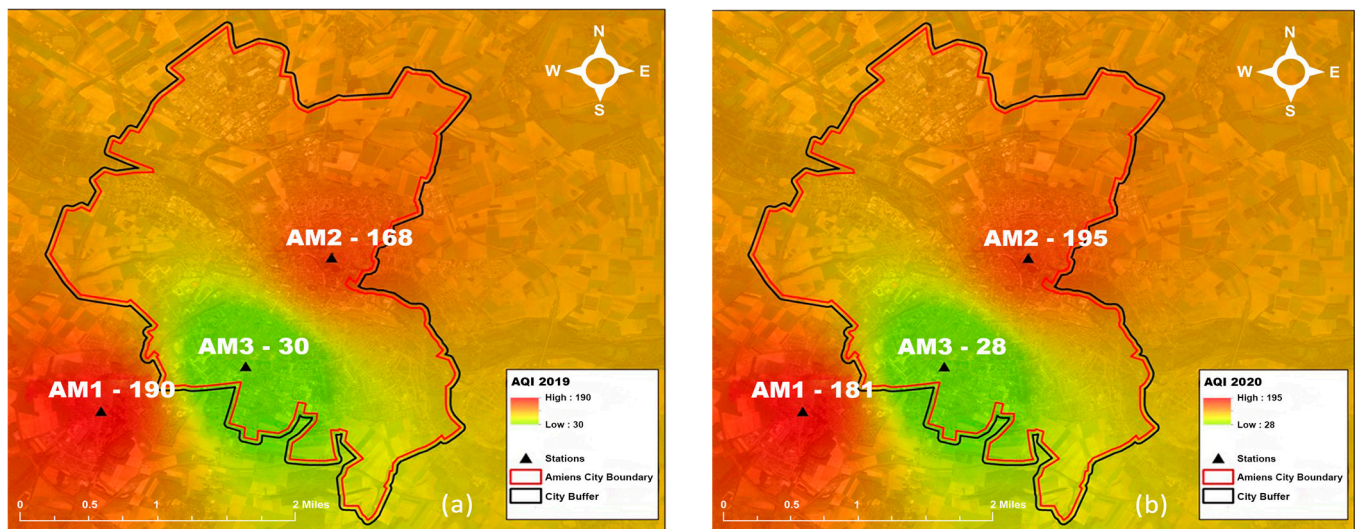


Figure 8. Air quality index maps created with the available data provided by a local agency (Atmo) (a) 2019 and (b) 2020.

## 2.2. Principal Component Analysis (PCA)

PCA is typically used in heat vulnerability studies to reduce the number of indicators. We applied this method in Stata v.16, which is an integrated statistical software package used for data analysis, management, and graphing. Stata's PCA was used to estimate the parameters of principal component models, where increasing variables and higher component scores indicated higher HVI. The 32 vulnerability indicators were grouped into five independent components. The variables in the components were allocated via the PCA algorithm [32].



### 3. Results

#### 3.1. Data Analysis

A linearity between extreme heat events and ground-level ozone concentrations was observed according to the recorded data at AM1 = 157  $\mu\text{g}/\text{m}^3$ , AM2 = 145  $\mu\text{g}/\text{m}^3$  on 25 July 2019 and at AM1 = 154.9  $\mu\text{g}/\text{m}^3$ , AM2 = 164.5  $\mu\text{g}/\text{m}^3$  on 31 July 2020 at 3:00 p.m.

After a detailed analysis, we observed that air temperature and ozone data were correlated with significant coefficient (0.8) at the abovementioned stations during the extreme heat days in 2019 and 2020. Due to missing air quality data, heat days in 2018 could not be compared with poor-air-quality events.

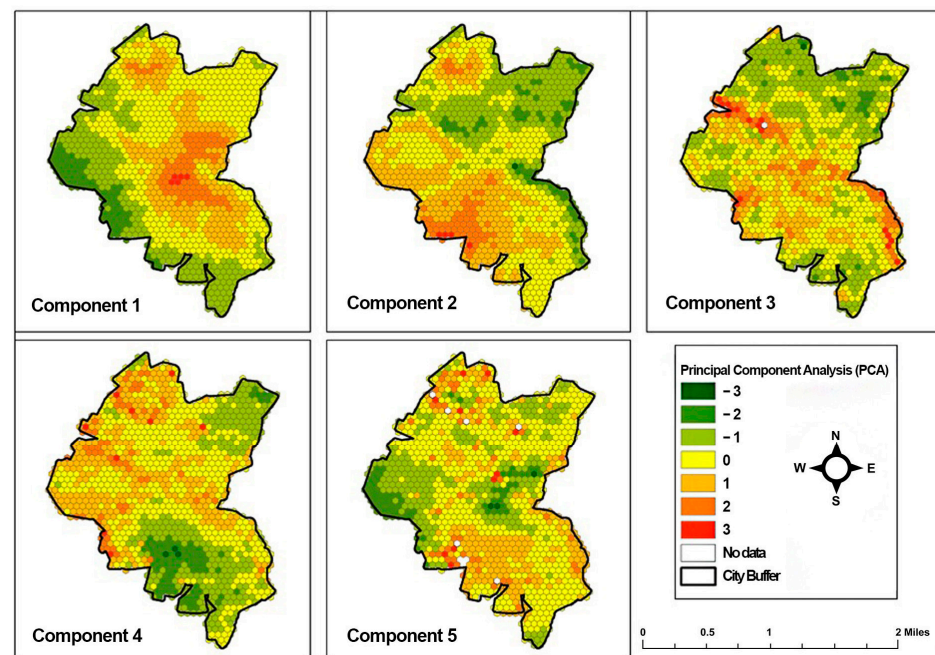
#### 3.2. Factor Scores

The factor scores were calculated, and it can be observed that the cumulative contribution of the components was 89.20%, which shows that the proportion of variance of the raw vulnerability indicators captured by PCs were explained by five independent components; for each variable, the sum of its squared loading across all PCs was equal to 1. Mathematically, the loadings were equal to the coordinates of the variables divided by the square root of the eigenvalues associated with the component. The first component explained 44.97% of the total variance, followed by 25.23%, 11.48%, 4.18%, and 3.34% for the second, third, fourth, and fifth components, respectively, as shown in Table 3.

**Table 3.** The cumulative contribution of variables.

Extraction Sums of Squared Loadings				
Factors	Eigenvalue	Difference	Proportion	Cumulative
1	14.39	6.31	0.45	0.44
2	8.07	4.40	0.25	0.70
3	3.67	2.33	0.11	0.81
4	1.34	0.27	0.04	0.85
5	1.07	0.26	0.03	0.89

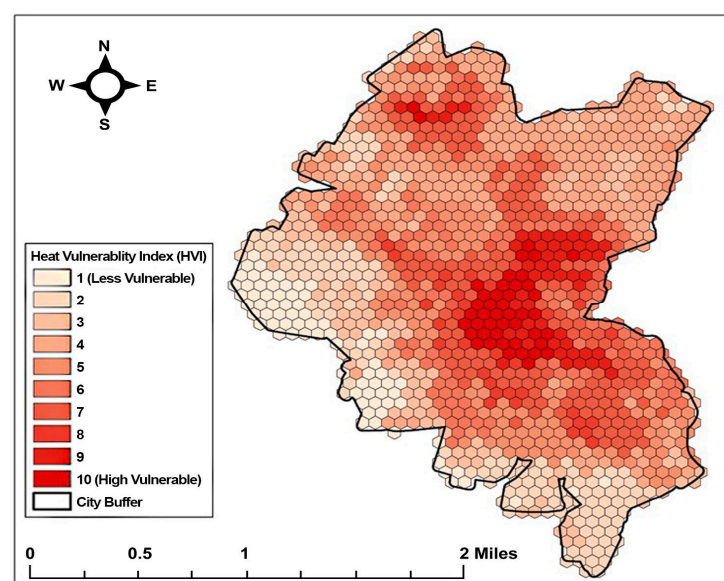
The first component included 22 variables (total population, no. of habitants aged  $\geq 65$  years, approximate no. of old habitants having asthma, cardiovascular diseases, and other respiratory diseases, no. of socially vulnerable people in the summertime, artificial surfaces in the city, area covered by vegetation, average AQI ( $\text{N}_2$ , NO,  $\text{O}_3$ ,  $\text{PM}_{10}$ ), illiteracy and poverty rates, and LST of extremely hot days recorded in 2019–2020). The second component was characterized by two variables (mean AQI calculated in the summers of 2019 and 2020). Component 3 was characterized by six variables (NDWI, NDVI, area covered by water bodies, LST of the hottest day in 2018, and summer mean LST of 2020). Components 4 and 5 were represented by the mean elevation and natural surfaces of Amiens, respectively. The merged vegetation was different from the NDVI, as well as the average AQI of each type of air pollutant. After aggregating components into the final HVI through different weight factors, the spatial distribution of HVI was obtained as shown in the map in Figure 9. The distribution of data for each point is provided in Table A2, where factor loadings of variables greater than  $\pm 0.6$  played an important role in the allocation of variables into defined components via PCA.



**Figure 9.** Map of components allocated by PCA algorithm.

### 3.3. Spatial Derivation Distribution of Heat Vulnerability Index (HVI)

HVI was derived from the sum of all components, and the resultant index map can be seen in Figure 10, where the accumulation of high scores shows that the city center is more vulnerable than rural areas. There may be several possible explanations for our result. The high number of elders and those living alone are concentrated in the city center. Meanwhile, there is a lack of awareness about extreme events and a high poverty rate in suburbs compared to the central area. Moreover, when asphalt is exposed to the sun, pavements start to soften, which can lead to delays and some roads being closed for traffic. This makes the city center more vulnerable to heat stress and poor-air-quality events. The agricultural land also has a high tendency to capture heat due to bare soil and harvesting grains, which causes an increase in HVI during extreme heat days of summer.



**Figure 10.** HVI map of Amiens indicating the greater vulnerability of the city center area to heat compared to the rural areas.

#### 4. Discussion

It has been observed that urban vulnerability is linked to various key factors, such as temperature, population, age, gender, literacy and poverty rate, and health-associated problems. It is estimated that, from 1999–2018, the global heat mortality rate increased by 53.7%, resulting in 296,000 deaths in 2018 [33]. By considering the local characters, six important factors were selected to construct the HVI using PCA. These key performance indicators were applied to identify susceptible regions vulnerable to heat waves, as well as population sensitivity and adaptation. This tool can assist in the planning of infrastructure and resources to reduce residents' vulnerability to extreme heat events, especially for the elderly population, since they are more vulnerable and at higher risk of heat-related deaths. The study also highlighted the influence of air pollution on heat events. However, the following limitations and challenges were faced during the development of HVI:

- Irregular and limited monitoring stations of weather and air quality;
- Lack of data from heating and cooling facilities.

The current case study provides a detailed methodology related to the impact of heat stress in the Amiens region, and this approach can be applied to the other regions for understanding the impact of heat waves, serving as a valuable tool for the development of HVI. In this study, our key emphasis was on investigating the adverse effects of strong heat waves on medium-sized cities. In Amiens, a medium-sized French city on which the 2003 heat wave had drastic impacts, it was reported that the annual mean temperature of this city has increased by +1 °C since 2000. A PCA-based novel approach was applied to study the fine-scale vulnerability mapping using various data types, and hotspot zones in the Amiens regions were identified using a comprehensive GIS mapping approach. The analysis identified the elevated HVI in three typical zones, i.e., population-dense and low-vegetation areas, as well as built-up and industrial zones. This was further linked with low vegetation cover, which is greatly responsible for the increasing temperature [34]. Moreover, it is also an established fact that industrialization is a major contributor to global warming [35]. By evaluating multiple covariates influencing the HVI, we are convinced that our current approach may be applicable to other regions of the world, including larger cities, to evaluate the heat-related vulnerabilities and help the authorities to take mitigation measures. Urban greenery and water bodies can be taken as existing cooling strategies; however, for better precision, district cooling consumption data should be considered in future.

#### 5. Conclusions

This work aimed to determine medium-sized city areas with higher heat vulnerability, which are more likely to experience high rates of morbidity and mortality on abnormally warm days. The parameters that influence current heat vulnerability were selected after data analysis and from the scientific literature. A strong relationship was noticed between heat and low air quality. This is a clear illustration of the system theory where anthropogenic activities appear in accordance with the extreme heat events in the city. The PCA technique was very helpful to derive the spatial HVI of the Amiens region. After analyzing the resulting maps, it was observed that the elevated HVI exists particularly in high-density built-up and industrial zones that release thermal energy and ozone at the ground level. A low HVI was located in natural landscapes such as rivers and grasslands. The developed methodology and maps can serve as a powerful tool for an assessment of the effect of extreme heat on vulnerable populations and for communication. It reveals the complex spatial and temporal patterns that would be difficult to interpret through text alone, allowing residents and local stockholders to visualize known areas of high HVI. It can also be influential in decisions to target resources for vulnerable populations to develop adaptation responses that promote resilience.

## 6. Recommendations

Data fusion techniques are recommended to collect data from multiple sources for analysis and development of HVI, thus increasing reliability and decreasing redundancy to support the decision-making process. This research sheds light on the following solutions that can help citizens to combat heat episodes:

- Information provision to local people about heat warnings and precautions, with more attention to vulnerable people;
- Implementation of proactive adaptive practices such as shades, blue infrastructure, and greenery where the HVI score is above 6;
- Regular monitoring during the summer season in the city.

**Author Contributions:** The paper was a collaborative effort between the authors. A.M.Q. and A.R. contributed collectively to developing the methodology of this study, analysis, development of HVI and the manuscript preparation. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** Not applicable

**Informed Consent Statement:** Not applicable

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Air quality monitoring and sensor's location.

Name Station	Address of Stations	City	Typology	Remarks
AM1	Rue Anatole France	Salouël	Peri-urban	-
AM2	Parc St Pierre rue Eloi Morel	Amiens	Urban dense	Stopped PM <sub>25</sub> monitoring in 2018
AM3	Avenue du 14 Juillet	Amiens	Traffic route	Stopped PM <sub>10</sub> and PM <sub>25</sub> monitoring in 2018

**Table A2.** Variable correlation magnitude with each component.

Variable	PC1	PC2	PC3	PC4	PC5	Uniqueness
NDWI	−0.3153	−0.4014	0.6994	−0.0494	0.116	0.2344
NDVI	−0.4412	−0.3843	0.5793	−0.2461	0.0486	0.2591
Total population	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Age ≥65	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Age ≥65 + asthma	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Age ≥65 + respiratory	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Age ≥65 + cardio	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Age ≥65 + living alone	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Artificial surfaces	0.7689	0.4482	0.0143	0.1858	0.0711	0.1682
Natural material	0.0125	0.1735	−0.1649	0.4099	0.6498	0.3523
Water bodies	−0.0301	−0.2768	0.5838	0.2811	0.113	0.4899
Merged vegetation	−0.6601	−0.343	−0.2613	−0.3114	−0.2607	0.2134
Wetlands	0.0924	−0.0937	0.6548	0.0701	0.2628	0.48
Mean_AQI_2019_avg_N <sub>2</sub>	0.7961	−0.5903	−0.0698	−0.0861	0.0679	0.0008
Mean_AQI_2019_avg_NO	0.7961	−0.5903	−0.0698	−0.0861	0.0679	0.0008
Mean_AQI_2019_avg_O <sub>3</sub>	−0.7961	0.5903	0.0698	0.0861	−0.0679	0.0008
Mean_AQI_2019_avg_PM <sub>10</sub>	−0.7961	0.5903	0.0698	0.0861	−0.0679	0.0008
Max_AQI_2019_Max_O <sub>3</sub>	−0.7877	0.6026	0.0795	0.0773	−0.0605	0.0006
Mean_AQI_2020_avg_N <sub>2</sub>	0.7961	−0.5903	−0.0698	−0.0861	0.0679	0.0008
Mean_AQI_2020_avg_NO	0.7961	−0.5903	−0.0698	−0.0861	0.0679	0.0008
Mean_AQI_2020_avg_O <sub>3</sub>	0.7961	−0.5903	−0.0698	−0.0861	0.0679	0.0008
Mean_AQI_2020_avg_PM <sub>10</sub>	−0.7961	0.5903	0.0698	0.0861	−0.0679	0.0008
Max_AQI_2020_Max_O <sub>3</sub>	0.8039	−0.5772	−0.0601	−0.095	0.0762	0.0021
Mean elevation	−0.199	0.257	−0.5217	−0.5109	0.1721	0.3316
Mean_AQI_2019	0.2481	−0.6447	−0.1689	0.5041	−0.3919	0.0865
Mean_AQI_2020	0.3431	−0.6756	−0.1677	0.4493	−0.3438	0.0777
Illiteracy	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
Poverty	0.8145	0.4883	0.2666	−0.0608	−0.1032	0.0128
LST hottest day 2020	0.5975	0.5702	−0.3591	0.1494	0.1406	0.147
LST hottest day 2019	0.6638	0.5418	−0.2211	0.1996	0.1399	0.1575
LST hottest day 2018	0.3725	0.3529	−0.6882	−0.0702	−0.0506	0.2555
LST summer mean 2020	0.509	0.5079	−0.6212	0.0583	0.0474	0.0915

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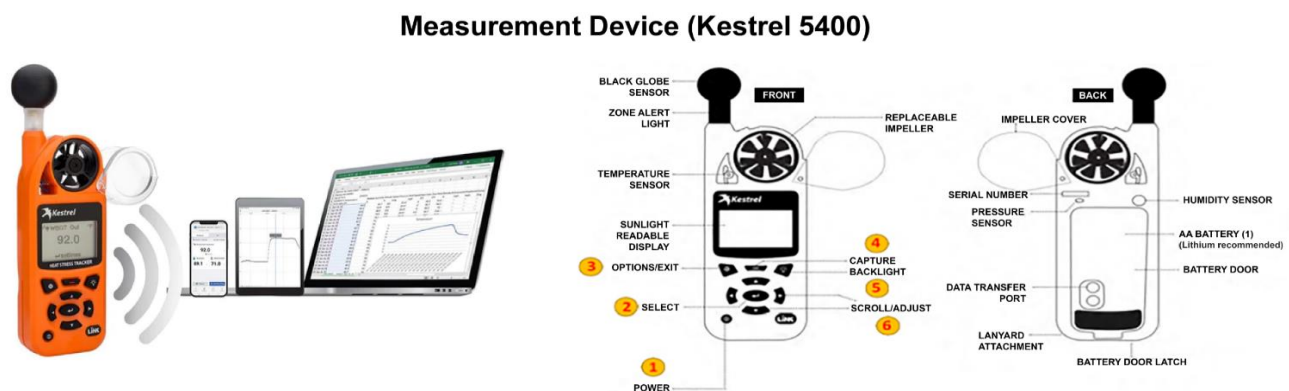


## Part - B

# Field Monitoring for Measuring the Cooling Effect

### 4.1 Location

Measurements were taken on August 4<sup>th</sup> and September 7<sup>th</sup> – 8<sup>th</sup>, 2021. The weather station named Kestrel 5400 [1], [2] shown in **Figure 4.1** was used to monitor the cooling impact of existing measures at three public places. In addition, measurement plan was prepared after selecting three pilot sites on foot in the city centre of Amiens, France. These sites are public open spaces where pedestrians and tourists often visit and use public benches. In the peak hours of a hot day, the shade of the trees and the surrounding measures such as water fountains, vegetation contributes to make the atmosphere pleasant by reducing the air temperature. Measurements were made to monitor the cooling impact of existing tree species at the chosen pilot sites. Furthermore, two 15 minutes rounds of monitoring were taken for all species on each day and each sample was recorded after every 10 seconds [3]. The measurement days were those when the sky was clear between peak hours (12:00 p.m. to 4:00 p.m.) and the position of the sun was southeast to southwest. Thermal images are captured prior to measurements with the FLIR E6 thermal camera.

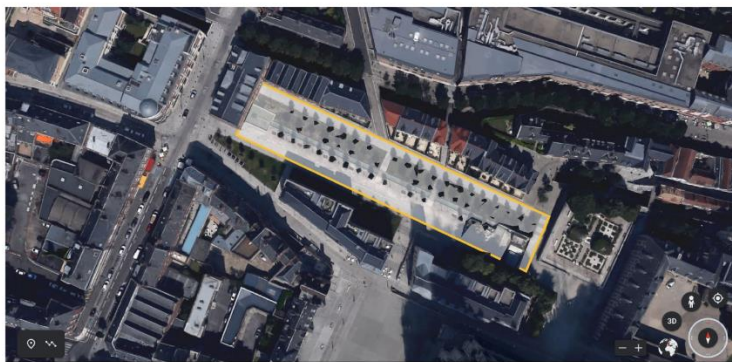


*Figure 4.1: Pictorial View of Monitoring Sensor and its Working*

Pilot's sites and existing features are briefly explained as follows:

**Pilot site 1:** The site was located near the cathedral of Amiens, it is a tourist place where a small water tunnel is surrounded by many trees of specie named *Tilia Cordata* Mill Malvaceae, roses and bushes. Two sensors were placed, one in the shade of a tree and the other placed 2m apart without any shade. The water tunnel was closed due to the Covid 19 pandemic to prevent the spread of the virus. The scaled map and the location of the reference sensor (no shade) and the point of intervention are shown in **Figure 4.2**.

### Pilot Site 1 Tree Specie = *Tilia Cordata* Mill Malvaceae



(a) Aerial view of site



(c) Thermal image of site



(b) Intervention and reference point setting



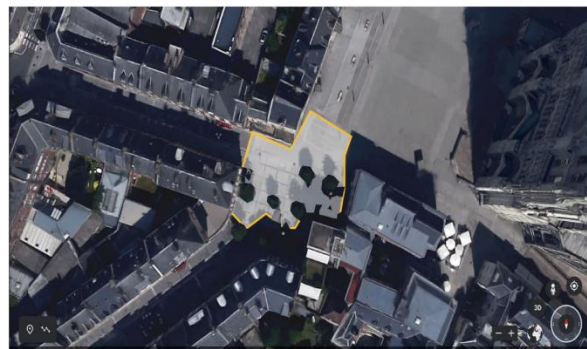
(d) Picture captured during measurement

**Figure 4.2:** Pilot site 1 at 34 rue des rinchevaux 80000 Amiens



**Pilot site 2:** The site was located on the left side of Amiens Cathedral, surrounded by a restaurant where tourists enjoy the existing shades of trees specie named *Tilia Platyphyllous* during hot sunny days. Two sensors were placed, one under the shade of a tree and the other 2m away without any shade. The scaled map and the location of the reference sensor (no shade) and the point of intervention are shown in **Figure 4.3**.

**Pilot Site 2**  
**Tree Specie = *Tilia Platyphyllous***



(a) Aerial view of site



(c) Thermal image of site



(b) Intervention and reference point setting

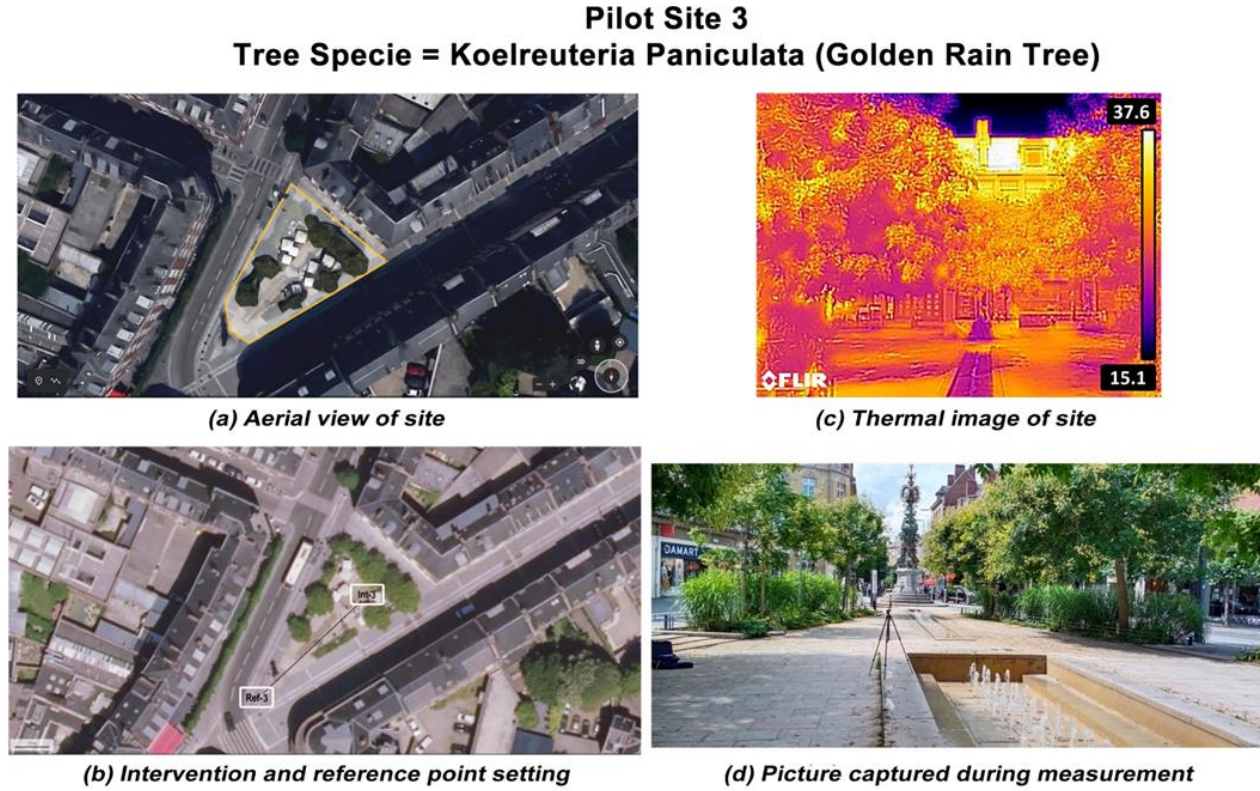


(d) Picture captured during measurement

**Figure 4.3: Pilot site 2 at 18 pl Notre-Dame 80000 Amiens**

**Pilot site 3:** It is a small triangular park located near a shopping centre in Amiens. The inhabitants of the city take advantage of this site during the summer season. Eleven trees of *Koelreuteria paniculata* (Golden Rain Tree) and lemongrass exist in this park. In addition, long water fountains give a pleasant environment by small water droplets with an extent of 8-10 m. Two sensors were placed, one under the

shade of a tree which was near the fountain and the second 8 m away without any shade. The scaled map and the location of the reference sensor (no shade) and the point of intervention are shown in **Figure 4.4**.



*Figure 4.4: Pilot site 3 at 6 rue dusevel 80000 Amiens*

## 4.2 Results and Discussion

The average cooling effect of these species was calculated by calculating the average value from the two monitoring cycles and by using the equation below:

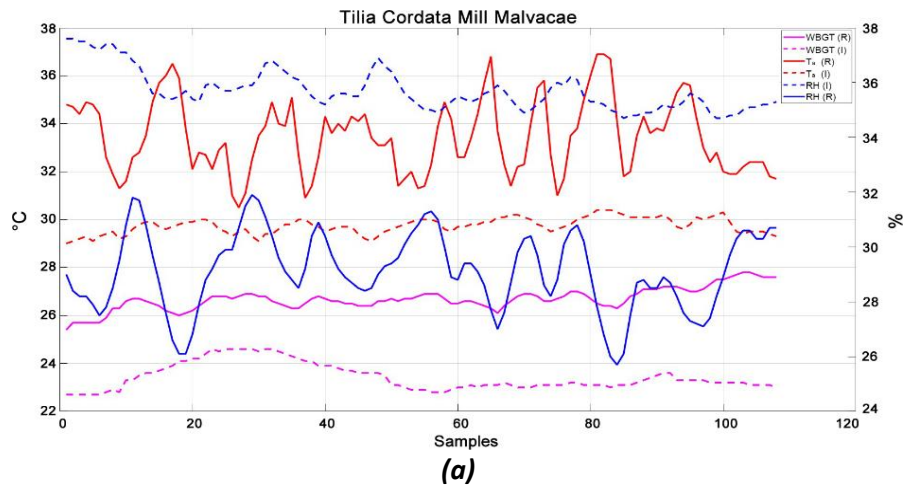
$$Q = A_R - A_I \quad \text{eq. (4.1)}$$

Where  $Q$  is cooling effect and  $A$  referred as variable such as  $RH$ ,  $T_a$  and  $R$  is measurements taken at reference point and  $I$  is the intervention point. The estimated average cooling effect for every 30 mins of each tree species is presented in **Table 4.1**. The recorded data for each site are plotted in **Figure 4.5**.

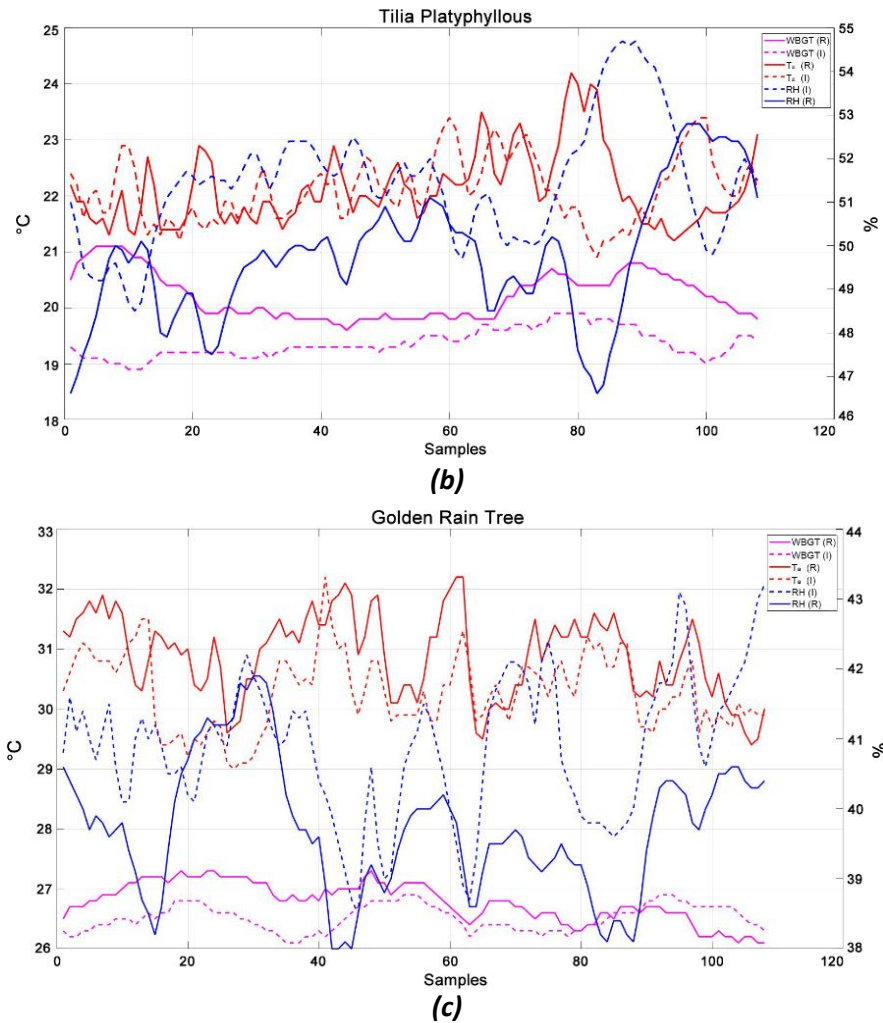
Table 4.1: Estimated Cooling Effect of Tree Species during Summer Season

Tree specie	$WBGT_{R-I}$ ( $^{\circ}\text{C}$ )	$RH_{R-I}$ (%)	$T_{aR-I}$ ( $^{\circ}\text{C}$ )
<b>Tilia Cordata Mill</b> <b>Malvaceae</b>	3.25	-6.58	3.7
<b>Tilia Platyphyllous</b>	0.86	-1.66	0.12
<b>Koelreuteria paniculata</b> <b>(Golden Rain Tree)</b>	0.27	-1.15	0.6

The estimated results showed that Tilia Cordata Mill Malvaceae was the effective species that improved thermal comfort by shading during hot days. In addition, the effectiveness obtained from Tilia Platyphyllous cannot be neglected; it was the cooling impact of a single tree with a span of 2-3 m. It increased humidity ( $RH$ ), which reduced the  $WBGT$ , however, an insignificant scale of air temperature ( $T_a$ ) decreased. Golden Rain Tree with the effectiveness of the water fountain was also effective due to its large cooling extent. Increasing humidity and decreasing  $T_a$  help to reduce thermal discomfort in a shopping area and increased attraction for visitors.







**Figure 4.5: Recorded Monitoring Data at Intervention (I) And Reference (R) Points for Species; (A) Tilia Cordata Mill Malvaceae (B) Tilia Platyphyllous (C) Golden Rain Tree**

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# Chapter – 5

## **Application of Multi-criteria Decision-making methods for Urban Heat Mitigation**

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This chapter is based on multi-criteria decision analysis to deal with heat stress. It consists of the following two parts:

- ❖ Part–A deals with Analytic Hierarchy Process for the selection of heat resilience measures.
- ❖ Part–B is based on the application of multiple methods and comparative analysis in terms of decision reliability for district heat mitigation

## Part - A

# An Analytic Hierarchy Process for Urban Heat Stress Mitigation

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The **part–A** of this chapter has been published as “An Analytic Hierarchy Process for urban heat stress mitigation” in (ICoDT2). This paper is attached at *Paper - IV* with kind permission from the conference publisher and can be cited as:

*Qureshi, A. M., & Rachid, A. (2022, May). An Analytic Hierarchy Process for urban heat stress mitigation. In 2022 2nd International Conference on Digital Futures and Transformative Technologies (ICoDT2) (pp. 1-6). IEEE. <https://doi.org/10.1109/ICoDT255437.2022.9787481>*

**Keywords:** Decision making approach; Analytic hierarchy process; Urban planning; Thermal comfort; Global warming

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### Major Findings

Analytic Hierarchy Process (AHP) approach is used for the selection of heat stress prevention measures. The applied technique assists to develop the key criteria framework that help the decision-making process in choosing appropriate measures for hotspots before implementing an intervention. The method was applied by pairwise comparison between the interventions to show the importance. The evaluation of the measures was based on the participants judgments, perception, and priorities through a questionnaire. Based on the survey inputs, it was found that the green roof is expensive, and the installation should follow the legal formalities, but it gives good cooling effect, has a significant impact on the environment and service life of the intervention is good and does not require additional maintenance compared to other but care. However, water fountains, misting should not be considered for implementation as it gives a short time cooling effect.

## **Paper - IV**

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# **An Analytic Hierarchy Process for Urban Heat Stress Mitigation**



# An Analytic Hierarchy Process for urban heat stress mitigation

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**Abstract**— In this study, an Analytic Hierarchy Process based approach is proposed for the selection of heat stress prevention measures. This approach provides decision makers with an easy way to evaluate the criteria that help the decision-making process in choosing appropriate measures for hotspots. The study focuses on the key pre-criteria before implementing an intervention. The proposed scheme is based on a comparison between the interventions to show the importance of the alternatives. The evaluation of the measures is obtained from a questionnaire where human judgment is used for a comparison, based on their perception and priorities. The final results showed that green roof is most beneficial option for heat stress mitigation with respect to criteria taken into account.

**Keywords**—: *Decision making approach, Analytic Hierarchy Process, urban planning, thermal comfort; global warming*

## I. INTRODUCTION

Due to global warming phenomena, it is notable that the atmosphere temperature is increasing over the years, and several problems are encountered related to this increase that must be addressed. A prolonged duration of extreme hot weather is called heat wave. Heat waves are one of the most dangerous problems related to global warming [1]. The frequency of heat waves is increasing over recent years, and it is spatially distributed around the world.

At this point the human body cannot be able to adapt itself to excessive exposure to temperature boundaries during heat waves and loses capacity to cool down. It leads to dehydration, hyperthermia, heatstroke and heat mortalities that might cause high quantities of heat-related sicknesses and deaths. In 1980, 10,000 individuals died in the United States because of a heat wave [2]. In July of 1995, it has executed more than 700 individuals in Chicago [3], and in August of 2003, more than 70,000 deaths were recorded in Europe [4]. Extreme heat has been observed to be the deadliest climate-related risk in certain areas [5]. Its widespread impacts on human health especially for vulnerable people for example citizens with respiratory, cardio, diabetes, mental disorder or other previous health problems. People, who are illiterate, older, with a low income, and socially disconnected, are likewise at more serious hazard.

In 2050 the part of worldwide urban population will grow by more than 68%. This implies that around 7 billion individuals are expected to live in urban zones [6]. Urban communities are the prevalent home spots for people to live and are more vulnerable to extreme weather conditions. The impact of heat stress could be prevented if proper measures are made. A few urban areas that have executed such measures have experienced decreases in the morbidity and mortality of heat-related illnesses [7]. A review of crisis reaction plans

found that half of the examined urban communities had some specific plans for extreme heat events [8]. However, it is hard for decision makers while choosing interventions for thermal comfort. Therefore, it is important to decide which plans and preventive measures to implement in order to reduce the harmful risks caused by heat stress. Modified and advanced urban planning strategies, green roofs and green facade walls, for example, can reduce the heat stress level and increase the outdoor thermal comfort

In previous studies team of researchers were focused on the several heat mitigation strategies. However, it is important to figure out the best measure which can improve thermal comfort especially in outdoor environment. This selection is quite difficult especially for decision makers due to the lack of sufficient data and unidentified principle of judgment. The main objective of this study is to suggest a benchmarking hierarchy which allows decision makers to think about different aspects and can help to identify the required data-gap of interventions and develop the decision support system on the principle of judgment.

This paper is organized as follows: section 2 contains a general review of heat preventive measures. Selection Process and proposed criteria are described in section 3 while section 4 presents the AHP tool and methodology. Results are discussed in the section 5 and finally, section 6 concludes this work and gives some perspectives.

## II. MEASURE OF BEST PRACTICE

There are several preventive measures which helps to decrease the heat stress in urban areas. In this study 5 best practice measures are considered for the application of the methodology which are summarized below in Fig.1.

## III. SELECTION PROCESS

An intervention selection procedure is an important tool that helps in decision of suitable measure at desire location. It empowers specialists to survey whether the thoughts and discoveries can be significant and reasonable. It allows decision makers to develop their criteria framework for alternatives to be applied on pilot sites. For this work, we found 5 general criteria that evaluates the outcomes as services and improvement in heat stress reduction. The criteria are defined below.

- Cost effectiveness:** In this study, we acknowledged capital and operational cost with future advancements.
- Efficiency:** defines the thermal comfort improvement in environment and intervention effectiveness within the time frame.

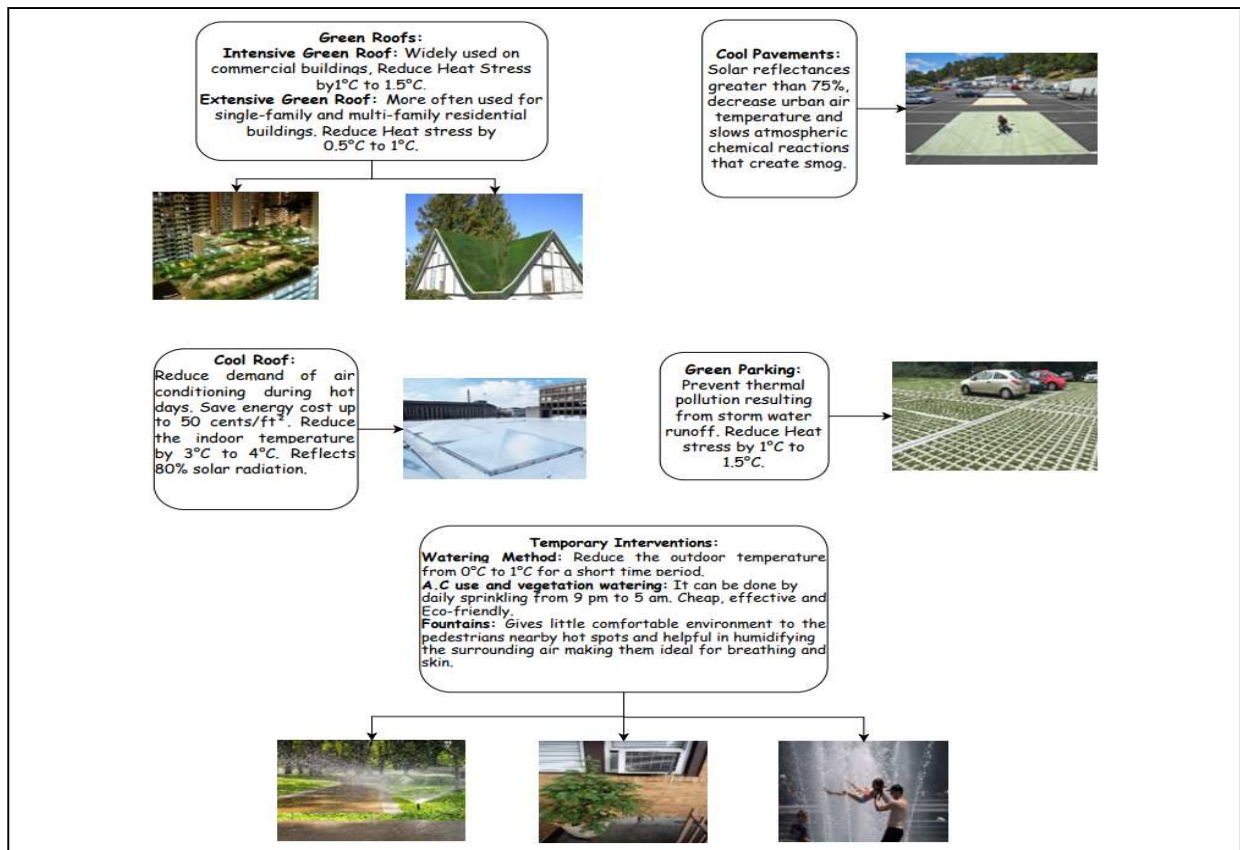


Fig.1 Best Practices measures to improve thermal comfort

- c. **Durability:** Criteria focuses on the toughness of intervention with the capable level of resisting heat and remain useful without demanding extra maintenance while coping with the heat events throughout the service life.
- d. **Environment Impact:** This criterion of investigation is a thorough statistical method for analyzing the impacts of man actuated or natural changes on the environment. By utilizing this intervention investigation, the real difference in the level of pollutants, land or water scarcity can be statistically obtained. For example, it might be essential to decide if a recently introduced intervention significantly reduces the previous mean level of a pollutant.
- e. **Legal:** Approval from authorities is necessary before planning and implementing the mitigation measure in cities

#### IV. ANALYTIC RESEARCH PROCESS

Analytic Hierarchy Process (AHP) is one of multi-criteria decision-making strategy that was initially created by Prof. Thomas L. Saaty [9]. It is a strategy to get proportion scales from combined examinations. The process is used for several fields of study until now, e.g. The method applied to evaluate the transport policies to reduce climate change impacts[10], An analysis of future water policies in Jordan [11], selection of electric power plants[12], contractor selection [13]. In this study AHP is implemented as a decision-making approach for the choosing intervention to mitigate the heat stress in urban areas under certain criteria. The hierarchy process is shown below in fig.2 and steps are explained in subsections. The information was obtained from specific

measures[14-15] for example, cost, efficiency, satisfaction feelings and preferences. Several questionnaires were filled by the research team and inputs obtained from these questionnaires are placed in the methodology. AHP permits some little irregularity in judgment that's called inconsistency

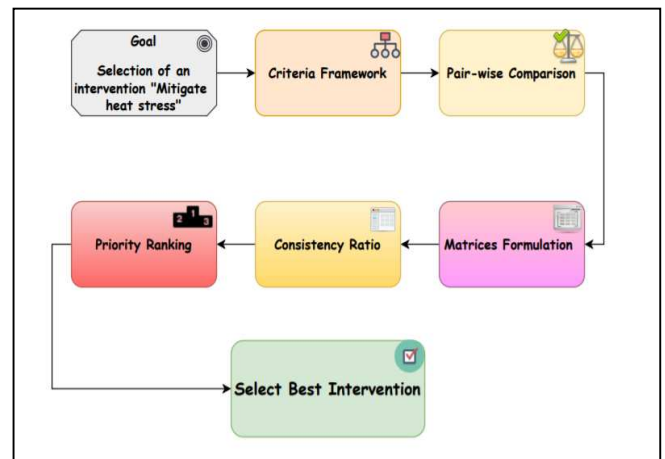


Fig.2 Analytic Hierarchy Process for Selection of an appropriate intervention to mitigate heat stress.

since human isn't always reliable but still, this method helps decision-makers to identify priorities through a pairwise comparison of alternatives.

##### A. Goal

The goal of this study is to select a preventive measure to reduce the heat stress in urban area. The goal of this study is to select a preventive measure to reduce the heat stress in urban area.

### B. Criteria framework

This step helps to construct the framework which expresses the aspects of the decision-makers' reflection on the desirable measure. The criteria framework is illustrated in Fig.3.

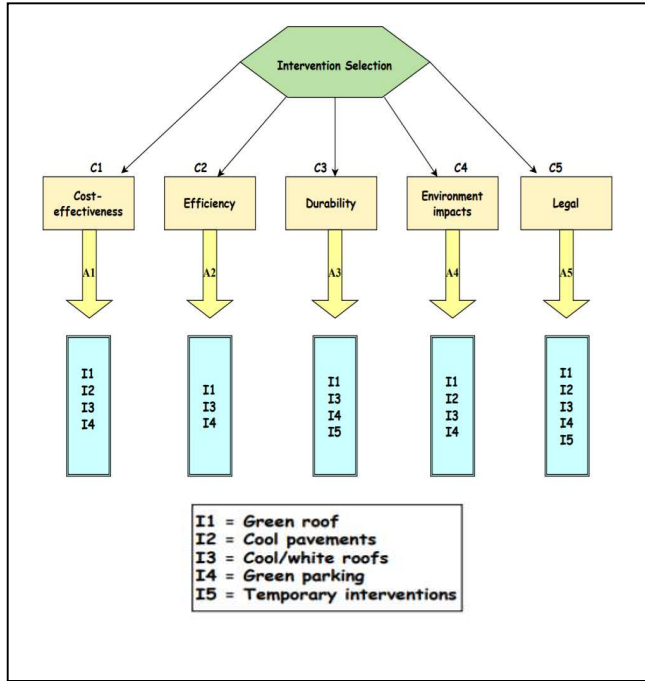


Fig.3 Criteria Framework along with important alternatives.

### C. Pair-wise Comparison

This step allows to compare the alternatives with all of them. Formation of pairs depends on the number of alternatives e.g. five criteria are considered for choosing best the intervention which improve the thermal comfort during hot summers. Hence, ten pairs for the criteria are calculated which are: (C1 – C2), (C1 – C3), (C1 – C4), (C1 – C5), (C2 – C3), (C2 – C4), (C2 – C5), (C3 – C4), (C3 – C5), (C4 – C5) with help of the formula shown in Table 1. Example of pairwise comparison between ‘Green Roof’ and Cool Pavements is shown in fig.4. The judgements are made with the help of scales recommended by Thomas Saaty, shown in Table.2

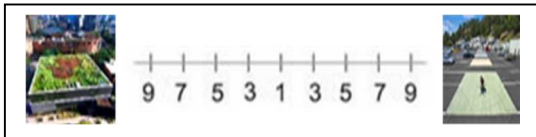


Fig.4 Example of pair-wise comparison between two intervention

Table1 Quantification of pairs

No. of interventions	No. of comparisons
1	0
2	1
3	3
4	6

5	10
6	15
7	21
$n$	$\frac{n(n-1)}{2}$

Table 2 Linguistic scale by Saaty

Values	Linguistic Scale
1	Equal importance
3	Moderate importance of one element over another
5	Strong importance of one element over another
7	Very strong importance of one element over another
9	Extreme importance of one element over another
2,4,6,8	Intermediate values compromise between two choices

### D. Matrices formulation

Outcomes of pair-wise judgment are formulated in matrices; diagonal elements of the matrix are always 1. The two following rules are used to create upper triangular matrix:

- If the judgment value is on the left side of 1, we put the actual judgment value.
- If the judgment value is on the right side of 1, we put the reciprocal value.

In order to set up the priority vector for criteria, AHP suggests an  $n \times n$  pairwise comparison of matrix A eq (1).

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} = (a_{ij})_{ij} \quad 1$$

Where  $a_{ij}$  is the element of row  $i$  column  $j$  of the matrix. The reciprocal values of the upper diagonal are used for lower triangular matrix. If the  $a_{ij}$  element of row  $i$  column  $j$  of the matrix, then the lower diagonal is filled using eq (2)

$$a_{ji} = \frac{1}{a_{ij}} \quad 2$$

After building the matrix A, the priority vector of criteria is calculated using the following steps:

- Normalization of pairwise comparison matrix  $A_{\text{norm}}$  is calculated by using eq (3) where the sum of the entries of each column is equal to 1 i.e  $\sum_{i=1}^n \bar{a}_{ij} = 1$

$$A_{\text{norm}} = \begin{pmatrix} \bar{a}_{11} & \cdots & \bar{a}_{1n} \\ \vdots & \ddots & \vdots \\ \bar{a}_{n1} & \cdots & \bar{a}_{nn} \end{pmatrix} = (\bar{a}_{ij})_{ij} \quad 3$$

- The matrix  $A_{\text{norm}}$  entries  $\bar{a}_{ij}$  are calculated using the entries  $a_{ij}$  of the matrix A using the eq (4)

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_{k=1}^n a_{kj}} \quad 4$$

- Priority vector of criteria is an n-dimensional column vector P and it is calculated by eq (5)

$$\Pi = \begin{pmatrix} P_1 \\ \vdots \\ P_n \end{pmatrix} \quad 5$$

Where priority vector is achieved by averaging the entries of each row of the matrix  $A_{\text{norm}}$  using the eq (5).

$$P_i = \frac{\sum_{k=1}^n a_{ik}}{n} \quad 6$$

#### E. Consistency Ratio

AHP suggests a consistency ratio (CR) technique based on testing. It is calculated by eq (7) which confirms that results are consistent with the provided judgments. If the consistency ratio value is  $\leq 10\%$ , the inconsistency is acceptable, but if the consistency ratio is  $\geq 10\%$  which means that the subjective preference assessment needs to be revised. The consistency index is called Random Consistency Index (CRI). Professor Saaty [9] provided the random indices shown in Table 3.

$$CR = \frac{CI}{RI} \quad 7$$

Where  $CI = \frac{\lambda_{\text{max}} - n}{n - 1}$  and  
 $\lambda_{\text{max}} =$   
 SOC 1(criteria weight of first row)  
 +SOC 2(criteria weight of second row+...

Table 3 Random index

no. of alternatives	Random index
1	0
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

#### V. RESULTS AND DISCUSSION

The participants choose the best-given options for the mitigation of heat stress in summers and their judgements are pair wisely compared and evaluate the importance of criteria over other. Afterward, judgments matrices are formulated to understand the priority vector. The results showed that environment impact is the most important (36.1%) criterion for the selection of an intervention which improves thermal comfort in urban areas, followed by the durability of measure on the desired location (30.8%). Efficiency (heat stress reduction level) is the third dominant criteria while deciding to implement nearby hotspots. Cost-effectiveness and Legal (permission by authority) are also essential criteria; however, it can be mold by investors and favorable arguments. The results of the questionnaire are illustrated in the pie diagram shown in Fig.5

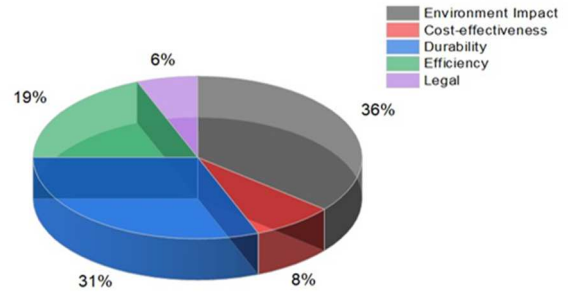


Fig.5 Pie diagram of Criteria Importance

#### A. Interventions Priority results with respect to Cost-Effectiveness

Cool pavements are 59.2% cost-effective option among all while cool/white roof is 26.5% effective concerning cost. The green roof is 9.9%, and green parking is 4.5% important, presented in Fig.6.

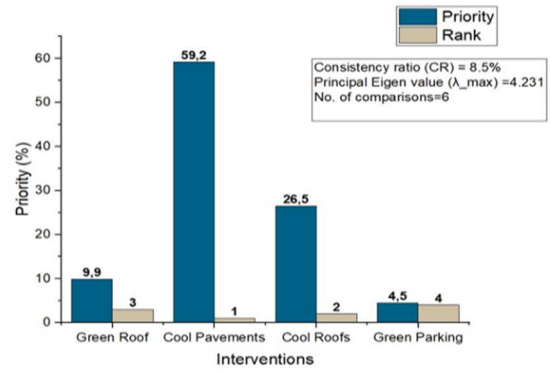


Fig.6 Interventions Correspond to Cost-effectiveness Priority Graph

#### B. Interventions Priority results with respect to Efficiency

The efficiency of alternatives is prioritized among the three major effective interventions are shown in Fig.7. A green roof is 64.9% efficient to reduce heat stress in the environment followed by green parking with, 27.9%, while cool roof is 7.2% important in terms of efficiency.

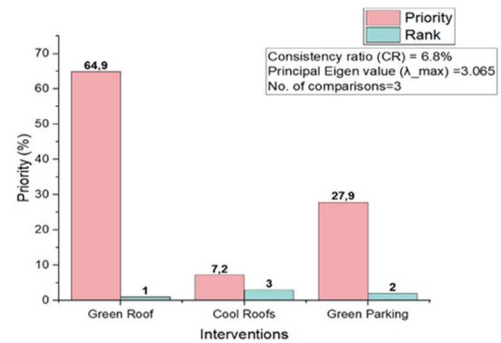


Fig.7 Interventions Correspond to Efficiency Priority Graph

#### C. Interventions Priority results with respect to Durability

According to the survey green roof is the most durable intervention by 54.9% for outdoor thermal comfort among the other alternatives shown in Fig.8. Green parking is second



ranked by 28.8% while cool roof is 11.5% and temporary interventions (watering method, fountain, other materials, etc...) are 4.8%.

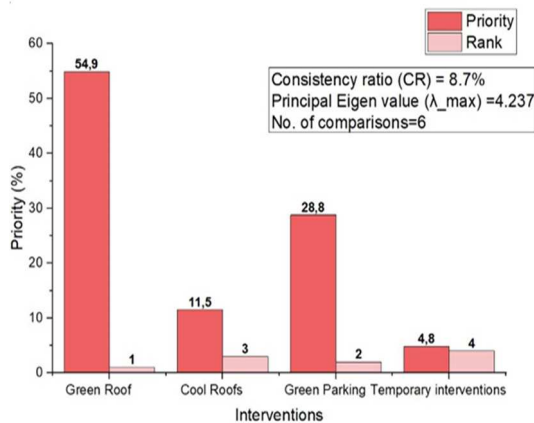


Fig.8 Interventions Correspond to Durability (a) Priority results (b) Priority Graph

#### D. Interventions Priority results with respect to environmental Impact

Environmental impact is high ranked criterion over all other standards as shown in Fig.5. Results are shown in Fig.9. Green roof is 56.2%, green-parking is 29.3%, 10.1% for cool/white roofs and cool pavement are 4.4% important over each other based on the aforementioned criterion.

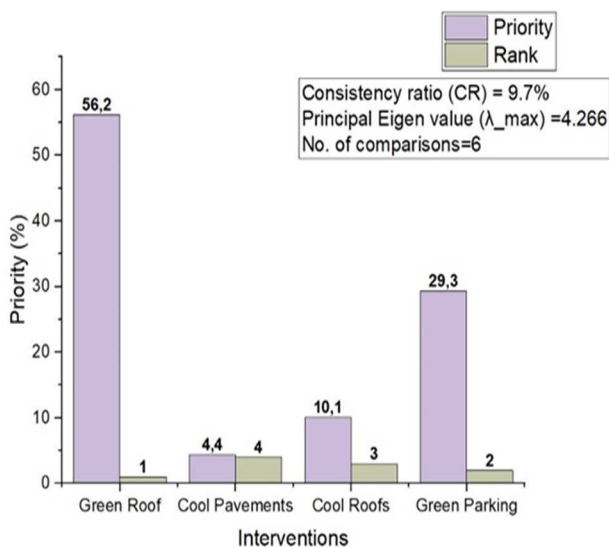


Fig.9 Interventions Correspond to Environment Impact Priority Graph

#### E. Interventions Priority results with respect to Legal aspects

Before implementing anything, it is necessary to have permission to respect the law. It is a valuable criterion for selection of intervention in the urban area, especially the city center and historical locations. However, it represents only 6% among other approaches that have been chosen. Considering this criterion before taking any action, it is needed to have legal permission for green-parking and green roof since both interventions are 38.7% and 37% important to legal criteria shown in fig.10. On the contrary, cool roofs (13.9%), cool pavements (5.6%) and temporary interventions (4.9%) are less valuable in terms of getting permission to be adapted.

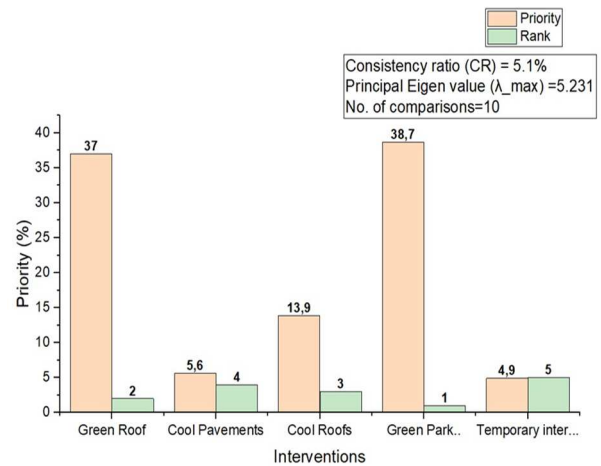


Fig.10 Priority Graph for Interventions Correspond to Legal criterion

#### F. Final Priority results with respect to all criteria

Interventions are ranked using eq (8). The final rankings are shown in Table.4. According to the survey entries, the green roof is expensive and the installation must meet the legal deadlines, but it gives a good cooling effect, has a significant impact on the environment, and the service life of the intervention is good and does not require additional maintenance but care. While interventions such as water fountains, misting, humidification of streets, use of air condition water for planting are temporary solutions that could be adapted to improve comfort but not solutions that can mitigate heat stress at the city level.

$$\sum_{n=R} = w(C_n I_n) \quad 8$$

Table 4. Final priority ranks

C/I	C1 0.08	C2 0.19	C3 0.31	C4 0.36	C5 0.06	Rank
I1	0.099	0.649	0.549	0.562	0.37	1
I2	0.592	0	0	0.044	0.056	4
I3	0.265	0.072	0.115	0.1	0.139	3
I4	0.045	0.279	0.288	0.293	0.387	2
I5	0	0	0.048	0	0.049	5

## VI. CONCLUSION

In this study, an AHP process is applied for the selection of an appropriate intervention to improve thermal comfort in small and medium cities. The pairwise comparison between the criteria and the judgments of the proposed intervention is assessed through a questionnaire based on the perception of the decision makers. The obtained results based on the survey entries showed that green roof is expensive and the installation must follow the legal formalities, but it gives a good cooling effect, has a significant impact on the environment, and the

service life of the intervention is good and does not require extra maintenance comparatively others but care. However, water fountains, misting shouldn't take in to account for implementation since it gives a cooling effect for time being. The ranking results presented in this article are given to illustrate the use of the proposed technique and must not be taken as universal. However, the same procedure could be followed and used in any location. It concludes that application of AHP in urban planning provides a useful decision support tool to local users and stakeholders.

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## Part - B

# Comparative Analysis of Multi-Criteria Decision-Making Techniques for Outdoor Heat Stress Mitigation

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The part of this chapter has been published as “Comparative Analysis of Multi-Criteria Decision-Making Techniques for Outdoor Heat Stress Mitigation” on journal “Applied Sciences” This paper is attached at

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### Major findings

In this chapter eight multi-criteria decision making methods namely Elimination and Choice Expressing Reality (ELECTRE) NI (Net Inferior), NS (Net Superior), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Vlekkriterijumsko KOMPromisno Rangiranje (VIKOR), Multi-Objective Optimization Ratio Analysis (MOORA), Weight Sum Method (WSM) and Weighted Product Method (WPM) are applied to select the heat mitigation measure under certain criteria. MCDMs were also coupled to the Analytic Hierarchy Process (AHP) where the AHP method is used to determine the weights of the selected criteria and the operational MCDMs are used to obtain the final ranking of the alternatives. This numerical research investigated the effectiveness of MCDM using different normalization techniques, the impact of their integrated model with AHP and highlight the limitations of the different MCDMs that reduce the reliability of the decision. It is found that WSM and PROMETHEE provides reliable and consistent under different normalization techniques. Additionally,

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the LnN was a more reasonable normalization technique, and it provided similar rankings in the majority of applied MCDMs. It was noticed that the coupling of AHP helped to minimize the frequency error through the pairwise method for criteria weights, which increased the reliability of the decision.

However, the priority of green walls and trees is an arbitrary output of decision makers. The ranking obtained on the parameters was not a general rule, and this procedure was carried out to check the reliability. The results were entirely based on the terrain, the perspectives, characteristics of the pilots, climatic conditions, and inputs of the decision-makers.

The improved frequency of consistent results by AHP-MCDM revealed that the ranking results mainly depended on the nature and the values of the criteria. The reasonable disagreement that was observed among the methods did not affect their reliability. As a result, MCDM models proved generally very effective for dealing with heat stress problems before their implementation and selection of the best ones.

**Keywords:** Heat stress; Multi criteria decision making; Analytic hierarchy process; Priority; Interventions



## **Paper - V**

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# **Comparative Analysis of Multi-Criteria Decision-Making Techniques for Outdoor Heat Stress Mitigation**

## Article

# Comparative Analysis of Multi-Criteria Decision-Making Techniques for Outdoor Heat Stress Mitigation

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**Abstract:** Decision making is the process of making choices by organizing relevant information and evaluating alternatives. MCDMs (Multi-Criteria Decision Methods) help to select and prioritize alternatives step by step. These tools can help in many engineering fields where the problem is complex and advanced. However, there are some limitations of the different MCDMs that reduce the reliability of the decision that needs to be improved and highlighted. In this study, Elimination and Choice Expressing Reality (ELECTRE) NI (Net Inferior), NS (Net Superior), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Vlekkriterijumsko KOMpromisno Rangiranje (VIKOR), Multi-Objective Optimization Ratio Analysis (MOORA), Weight Sum Method (WSM) and Weighted Product Method (WPM) are applied for the selection of urban heat mitigation measurements under certain criteria. The models were applied using weighting criteria determined by two ways, (i) the direct weighting method and (ii) the Analytic Hierarchy Process (AHP), for precise weighting factoring through pairwise comparison. This numerical research evaluated the reliability of MCDMs using the same decision matrix under different normalization techniques and shows the impact of AHP on the decision. The results show that WSM and PROMETHEE provided reliable and consistent results for all normalization techniques. The combination of AHP with applied MCDMs improved the frequency of consistent ranking, except with ELECTRE-NS.

**Keywords:** heat stress; multi criteria decision making; analytic hierarchy process; priority; interventions



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## 1. Introduction

Multi-criteria Decision Methods (MCDMs) are valuable tools to handle the selection problem. They are based on five components, which are: goals, thoughts of the specialist, alternatives, criteria, and results. The MCDM requires human recognitions as sources of information where uncertainty and subjective aspects exist. The decision maker's assessments can be expressed by using linguistic terms such as “low importance” or “brilliant performance”. The idea of these assessments is often subjective because some criteria that do not have an objective measure, which forces the decision makers to express their thoughts using numeric scales. There are many MCDM methods which are used in different fields of study; for example, the Previously Fuzzy logic method [1] has been applied in the soil sciences [2], supplier's performance [3], for imprecise information related to distribution problems [4], in the field of accounting and finance to develop guidelines for investment decisions [5,6], and in the selection of the appropriate process performance [7]. However, the fuzzy logic method has no potential to measure the level of consistency in the judgments provided by a decision maker.

AHP is a one of the oldest and most trusted decision-making methods [8]. It is a comprehensive technique that has ability to solve the complex decision-making problems by assembling, quantifying, and evaluating the alternative solution through hierarchies [9,10]. Furthermore, it is easy to implement by experts of other fields and overcomes the resulting risk of inconsistency. Consistency plays a vital role in AHP. When the consistency ratio

of the pairwise comparison matrix is greater than 10%, it requires a review of the inputs to make the results consistent with the provided judgments [11]. The modified version of Fuzzy-AHP is aimed at removing the vagueness and uncertainty in decision-making, but due to heavy calculations and a high risk of errors, it is difficult to adapt. In contrast, the conventional AHP is quite easy to update, completely reliable, and cost effective, and its analysis can easily be performed by software [12,13]. Previously, the AHP was coupled with other MCDMs, such as MOORA for public transport service quality [14], ELECTRE for personnel selection [15], TOPSIS for the evaluation of knowledge sharing capabilities of supply chain partners [16] and suitable technology transfer strategy for wind turbines [17], PROMETHEE for the selection of policy scenarios for vehicle fleet [18], VIKOR for the assessment of school teachers [19], WSM to evaluate the knowledge in supply chain patterns [20], and WPM for the selection of open-source electronical medical records [21]. In one research, the DEA model was used to assess the performance of small- to medium-sized manufacturing enterprises, and it showed that the MCDM model combined with the AHP was more consistent than stand-alone models where the decision was entirely based on quantitative inputs [22]. The main reason why many companies do not rely on MCDM methods can be due to the fact that decision makers intuitively notice ranking errors [23]. However, there is a need to determine the comparative study on the reliability of the MCDMs. So far, the application of several MCDMs and their comparative study in the field of Urban Heat Stress (UHS) has not been carried out due to long reasoning, which is difficult to quantify and scale. This research is based on the selection of interventions to mitigate outdoor heat stress by using different multicriteria decision applications, such as PROMETHEE, VIKOR, MOORA, ELECTRE (NS, NI), TOPSIS, WPM, and WSM. The applied methods are also combined with AHP, which identifies the effectiveness of standalone application using direct criteria weightage and the impact of AHP on the decision process in field of UHS. The impact of different normalization methods and coherent frequency in ranking results obtained from the application of different MCDMs are also investigated.

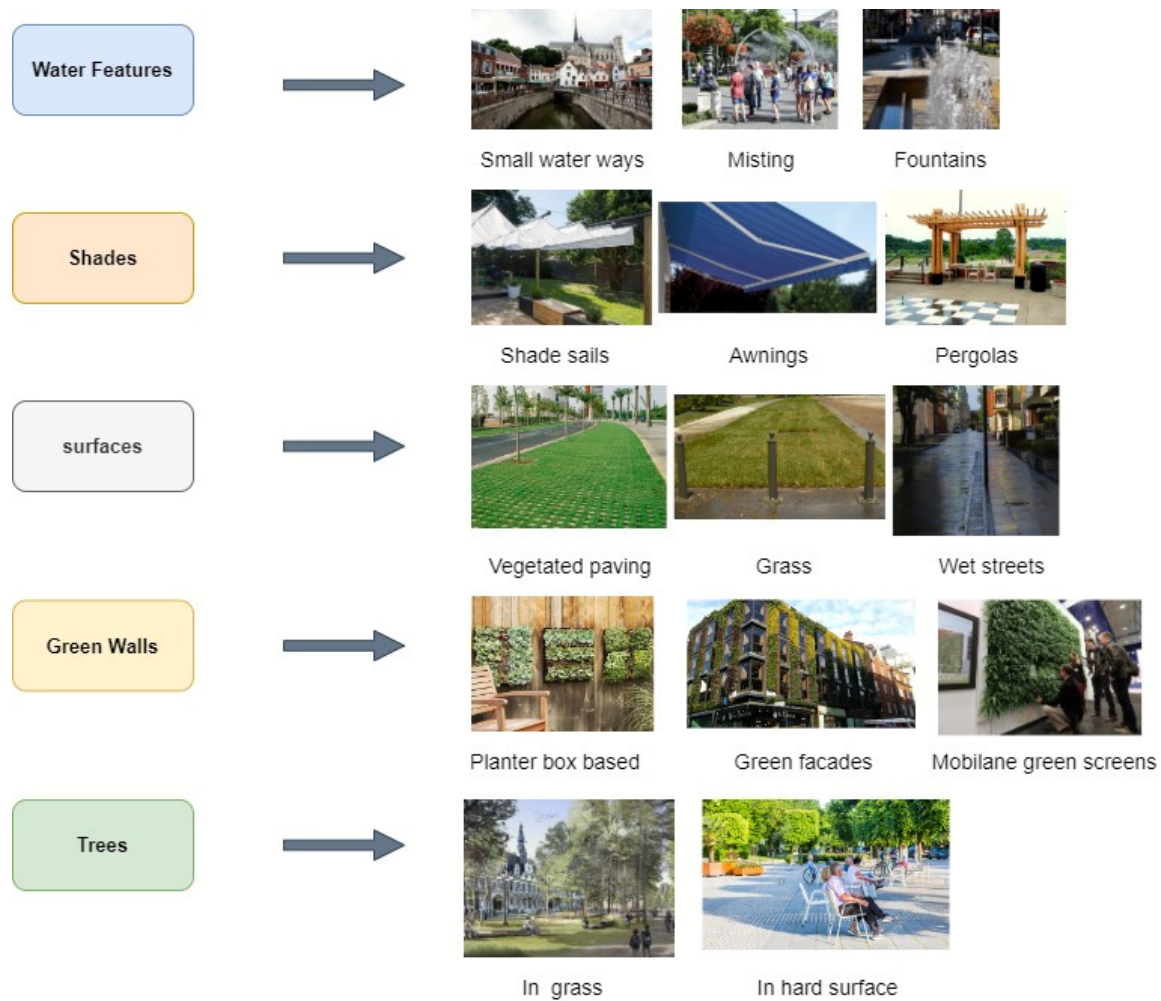
The article is organized as follows. Section 2 presents the research background and related work. The underlying concepts and mathematical formulas are given in Section 3. The research methodology is explained in Section 4. Sections 5 and 6 provides the simulation results and discussion. The article ends with a conclusion and some perspectives.

## 2. Research Background

UHS is the current crucial concern for scientists and residents of medium- and large-sized cities, which are at more risk for heat events. Prolonged exposure can cause heat exhaustion, cramps, stroke, as well as exacerbate pre-existing chronic conditions, such as various respiratory, cerebral, and cardiovascular diseases, especially for vulnerable people. There are many heat mitigation strategies for improving thermal comfort in urban areas. As human beings, it is our sacred duty to save the environment in which we live, but decision maker responsibility is much bigger because many remedial measures need to be implemented on a large scale. The application of MCDMs could be first approach that assists decision makers to quantitatively assess the importance of criteria and the performance of alternatives in selection processes.

In previous studies, AHP-SWOT, multi-criteria outranking approach, EFDM, FDEMATL, multi-criteria method by linear regression, TOPSIS, SMCE, Fuzzy-AHP TOPSIS have been used in the field of UHS [24]. In addition, the AHP method was specifically used to select the urban heat resilience intervention under certain criteria [25].

From the literature, it was investigated that most popular interventions considered to deal with thermal stress are white roofs, extensive green roofs, intensive green roofs [26], planting trees in cities [27], green parking lots, cool roofs, watering methods (sprays in public areas) [28], green walls, and shades. Figure 1 shows the interventions chosen for this study that can mitigate thermal discomfort in an urban setting.



**Figure 1.** Type of heat resilience interventions.

For our studies, we considered four general criteria to address for the selection process of interventions (alternatives). These criteria are the following:

- *Cost*: capital and running cost of the intervention, which is often taken as a non-beneficial (NB) criterion.
- *Environment*: impact of the intervention on the level of air, land, and water. For example, it might be necessary to know if a recently introduced intervention significantly improves the previous mean level of air quality.
- *Efficiency*: cooling effect of intervention in open spaces.
- *Durability*: intervention capability to withstand the level of heat and remain useful without requiring additional maintenance after extreme weather events throughout the service life.

### 3. Mathematical Models of MCDMs

Eight different MCDMs and seven normalization methods were computed for deciding the UHS mitigation intervention. Additionally, the AHP was also applied for calculating the weightage of criteria. The procedure and key equations of methods are given in Table 1. Mathematical formulas of applied normalized methods are presented in Table 2.

**Table 1.** Key equations of MCDMs used in this study.

MCDM	Steps	Reference
TOPSIS: Technique for Order Preference by Similarity to Ideal Solutions	Step 1: make decision matrix	[29]
	Step 2: normalize decision matrix	
	Step 3: weighted normalized decision matrix	
	$r_{ij}$ : normalized decision matrix	
	$V_{ij} = w_j r_{ij}$	
	$w_j$ : weight of the $j$ th criteria (attribute)	
	Condition $\sum_{j=1}^n w_j = 1$	
	Step 4: ideal best $V_j^+$ and ideal worst $V_j^-$ values	
	If beneficial criteria:	
	$V_j^+ = \max_i (v_{ij}) = \max \{v_{ij}, i = 1, \dots, m\}$	
ELECTRE(NI-NS): Elimination and Choice Expressing Reality	If cost criteria:	[30]
	$V_j^- = \min_i (v_{ij}) = \min \{v_{ij}, i = 1, \dots, m\}$	
	Step 5: Calculate the distances of each alternative from the positive ideal solution and the negative ideal solution	
	$S_i^\pm = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^\pm)^2}$	
	Step 6: Calculate the relative closeness to the ideal solution (performance score)	
	$R_i = \frac{S_i^-}{S_i^+ + S_i^-}$	
	Step 7: Ranking the best alternative	
	Step 1: make decision matrix	
	Step 2: normalize decision matrix	
	Step 3: weighted normalized decision matrix	
	$v_{ij} = R \times W = \begin{vmatrix} r_{11} \cdot W_1 & r_{12} \cdot W_2 & K & r_{1n} \cdot W_n \\ r_{21} \cdot W_1 & r_{22} \cdot W_2 & K & r_{2n} \cdot W_n \\ K & K & K & K \\ r_{m1} \cdot W_1 & r_{m2} \cdot W_2 & K & r_{mn} \cdot W_n \end{vmatrix}$	
	Step 4: concordance and discordance interval sets	
	$C_{ab} = \{j \mid v_{aj} \geq v_{bj}\}$	
	$D_{ab} = \{j \mid v_{aj} < v_{bj}\} = J - C_{ab}$	
	Step 5: calculation of the concordance interval matrix	
	$C_{ab} = \sum_{j \in C_{ab}} W_j$	
	$C = \begin{vmatrix} - & c(1,2) & \dots & c(1,m) \\ c(2,1) & - & \dots & c(2,m) \\ \vdots & \vdots & \vdots & \vdots \\ c(m,1) & c(m,2) & \dots & - \end{vmatrix}$	
	Step 6: Determine the concordance index matrix	
	$\bar{c} = \frac{\sum_{a=1}^m \sum_{b=1}^m c(a,b)}{m(m-1)}$	
	$e(a,b) = 1$ if $c(a,b) \geq \bar{c}$	
	$e(a,b) = 0$ if $c(a,b) < \bar{c}$	
	Step 7: Calculation of the discordance interval matrix	
	$d(a,b) = \frac{\max_{j \in D_{ab}}  v_{aj} - v_{bj} }{\max_{j \in J_{mn}}  v_{aj} - v_{bj} }$	
	$D = \begin{vmatrix} - & d(1,2) & \dots & d(1,m) \\ d(2,1) & - & \dots & d(2,m) \\ \vdots & \vdots & \vdots & \vdots \\ d(m,1) & d(m,2) & \dots & - \end{vmatrix}$	

Table 1. Cont.

MCDM	Steps	Reference
	Step 8: determine the discordance index matrix $\bar{d} = \frac{\sum_{a=1}^m \sum_{b=1}^m d(a,b)}{m(m-1)}$ $f(a,b) = 1 \text{ if } d(a,b) \leq \bar{d}$ $f(a,b) = 0 \text{ if } d(a,b) > \bar{d}$ Step 9: calculate the net superior and inferior value $C_a: \text{ net superior}$ $C_a = \sum_{b=1}^n C(ab) - \sum_{b=1}^n C(ba)$ $d_a: \text{ net inferior}$ $d_a = \sum_{b=1}^n d(ab) - \sum_{b=1}^n d(ba)$ Step 10: select the best alternative choose highest value of net superior ( $C_a$ ) and lowest value of net inferior ( $d_a$ )	
PROMETHEE: This method utilizes a preferential function to drive the preference difference between alternative pairs.	Step 1: decision matrix Step 2: normalized the decision matrix Step 3: deviation by pairwise comparison $d_j(a,b) = R_j(a) - R_j(b)$ Step 4: preference function $p_j(a,b) = 0 \text{ if } d_j(a,b) \leq 0$ $p_j(a,b) = d_j(a,b) \text{ if } d_j(a,b) > 0$ Step 5: multi-criteria preference index $pi_j(a,b) = \sum_{j=1}^n p(a,b)W_j$ Step 6: positive and negative outranking flows ( $a \neq b$ ) $\Phi^+(a) = \frac{1}{m-1} \sum_{b=1}^n pi(a,b)$ Step 7: net flow $\Phi = \Phi^+ - \Phi^-$ Step 8: Ranking the best alternative by using highest value of net flow	[31]
VIKOR: multi-criteria optimization and compromise solution which focuses on ranking and selecting from a set of alternatives in the presence of conflicting criteria.	Step 1: Determine the objective and identify the pertinent evaluation attributes. Step 2: normalized decision matrix $f$ Step 3: Find best and worst Best: $f_j^+ = (f_{ij})_{\max} = \max_i (f_{ij}) \text{ Beneficial attribute}$ $f_j^- = (f_{ij})_{\min} = \min_i (f_{ij}) \text{ Non beneficial attribute}$ Worst: $f_j^- = (f_{ij})_{\min} \text{ Beneficial attribute}$ $f_j^+ = (f_{ij})_{\max} \text{ Non beneficial attribute}$ Step 4: utility measure $S_i$ and regret measure $R_i$ $S_i = \sum_{j=1}^n w_j \left[ \frac{f_j^+ - (f_{ij})}{f_j^+ - f_j^-} \right]$ $R_i = \max_j \left\{ w_j \left[ \frac{f_j^+ - (f_{ij})}{f_j^+ - f_j^-} \right] \right\}$ Step 5: calculate the value of $Q_i$ $Q_i = v \left[ \frac{S_i - (S_i)_{\min}}{(S_i)_{\max} - (S_i)_{\min}} \right] + (1-v) \left[ \frac{R_i - (R_i)_{\min}}{(R_i)_{\max} - (R_i)_{\min}} \right]$ $v = 0 \dots 1 \text{ generally taken as } 0.5$ Step 6: ranking the best alternative with lowest value of $Q_i$	[32]

Table 1. Cont.

MCDM	Steps	Reference
MOORA: Multi-Objective Optimization on the Basis of Ratio Analysis	Step 1: The alternatives and attributes values in the decision matrix: Step 2: Normalize decision matrix Step 3: positive and negative effects: maximization for beneficial criteria, minimization for non-beneficial (cost)	[33]
	$yb_i = \sum_{j=1}^g x_{ij}^* w_j$ $ynb_i = \sum_{j=1}^{n-g} x_{ij}^* w_j$ $y_i = yb_i - ynb_i$ $y_i = \sum_{j=1}^g x_{ij}^* w_j - \sum_{j=1}^{n-g} x_{ij}^* w_j$ Where alternative has the 1st rank with highest value of $y_i$	
WSM: Weighted Sum Method	Step 1: make decision matrix. Step 2: normalized decision matrix Step 3: weighted normalized decision matrix $r_{ij}$ : normalized decision matrix $v(i, j) = r(i, j) \cdot w(j)$ Step 4: weighted sum $ws(i) = \sum_{j=1}^n v(i, j)$ Step 5: ranking the best alternative	
	Step 1–3: same as WSM Step 4: weighted product $wp(i) = \prod_{j=1}^n v(i, j)$ Step 5: ranking the best alternative	
WPM: Weighted Product Method	Step 1: Pair-wise comparison matrix of criteria or alternatives $P(i) = \prod_{j=1}^n A(i, j)$ $Pn(i) = (P(i))^{1/N}$ $Pn(i) = \left( \prod_{j=1}^n A(i, j) \right)^{1/N}$ $sp = \sum_{i=1}^m Pn(i)$ Step 2: Criteria weights or alternatives scores: $w(i) = Pn(i) / sp$ Step 3: Calculate consistency $w(i) = w(j)$ , where $n = m$ size of A matrix $v(i, j) = x(i, j) \cdot w(j)$ Step 4: calculate weighted sum value: $sw(i) = \sum_{j=1}^n v(i, j)$ Step 5: calculate consistency error $R(i) = sw(i) / w(i)$ $\lambda \sum_{i=1}^m R(i) / m_{max}$ $CI = \frac{\lambda_{max} - n}{n - 1}$ For $n = 4$ , $Ri = 0.9$	[34]



**Table 2.** Mathematical formulas of different normalization methods.

Normalization	Abbreviation	Beneficial	Non-Beneficial
Linear	L <sub>N-i</sub>	$\bar{X}_{ij} = \frac{X_{ij}}{X_j^{max}}$	$\bar{X}_{ij} = 1 - \frac{X_{ij}}{X_j^{max}}$
	L <sub>N-ii</sub>	$\bar{X}_{ij} = \frac{X_{ij}}{X_j^{max}}$	$\bar{X}_{ij} = \frac{X_j^{min}}{X_{ij}^{min}}$
	L <sub>N-max-min</sub>	$\bar{X}_{ij} = \frac{X_{ij} - X_j^{min}}{X_j^{max} - X_j^{min}}$	$\bar{X}_{ij} = \frac{X_j^{max} - X_{ij}}{X_j^{max} - X_j^{min}}$
	L <sub>N-Sum</sub>	$\bar{X}_{ij} = \frac{X_{ij}}{\sum_{i=1}^m X_{ij}}$	$\bar{X}_{ij} = \frac{\frac{1}{X_{ij}}}{\sum_{i=1}^m (\frac{1}{X_{ij}})}$
Enhanced accuracy	E <sub>AN</sub>	$\bar{X}_{ij} = 1 - \frac{X_j^{max} - X_{ij}}{\sum_{i=1}^m (X_j^{max} - X_{ij})}$	$\bar{X}_{ij} = 1 - \frac{X_{ij} - X_j^{min}}{\sum_{i=1}^m (X_{ij} - X_j^{min})}$
Logarithmic	L <sub>nN</sub>	$\bar{X}_{ij} = \frac{\ln X_{ij}}{\ln(\prod_{i=1}^m X_{ij})}$	$\bar{X}_{ij} = 1 - \frac{1 - \frac{\ln X_{ij}}{\ln(\prod_{i=1}^m X_{ij})}}{m-1}$
Vector	V <sub>N</sub>	$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}}$	$\bar{X}_{ij} = 1 - \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}}$

#### 4. Research Methodology

The collection of human perspectives is the first step for implementing any MCDM. The survey was distributed with the explanation of the purpose of the study. Participants were asked to participate in quantitative judgment using the linguistic scale, shown in Figure 2, to assess the importance of criteria and the performance of alternatives (interventions) for UHS mitigation. The experts belonged to academics in the field of urban climate.

1	2	3	4	5	6	7	8	9	10
Very Low		Low		Medium		High		Very High	

**Figure 2.** Linguistic scale for rating the importance of criteria and performance of alternatives.

The collected questionnaires were checked, and assessments that contained inconsistencies were discarded and not used for further analysis. After this quality check, it was observed that 25 ratings could be useful. These judgments were aggregated using geometric means and then MCDMs, such as ELECTRE-NS, ELECTRE-NI, MOORA, PROMETHEE, TOPSIS, VIKOR, WPM, and WSM, were applied to prioritize the UHS mitigation alternatives (A1, A2 ...). These methods were implemented in two ways: stand-alone, where direct criteria weights were used, and coupled with AHP (criteria weights calculated by AHP using the judgment matrix shown in Table 3). Seven different normalization methods were used for the simple application of MCDMs (stand-alone). The research methodology is shown in Figure 3.

**Table 3.** Criteria weight matrix by AHP.

Criteria	Cost	Efficiency	Durability	Environment Impacts
Cost	1	2	3	2
Efficiency	1/2	1	2	1
Durability	1/3	1/2	1	1/2
Environment	1/2	1	2	1



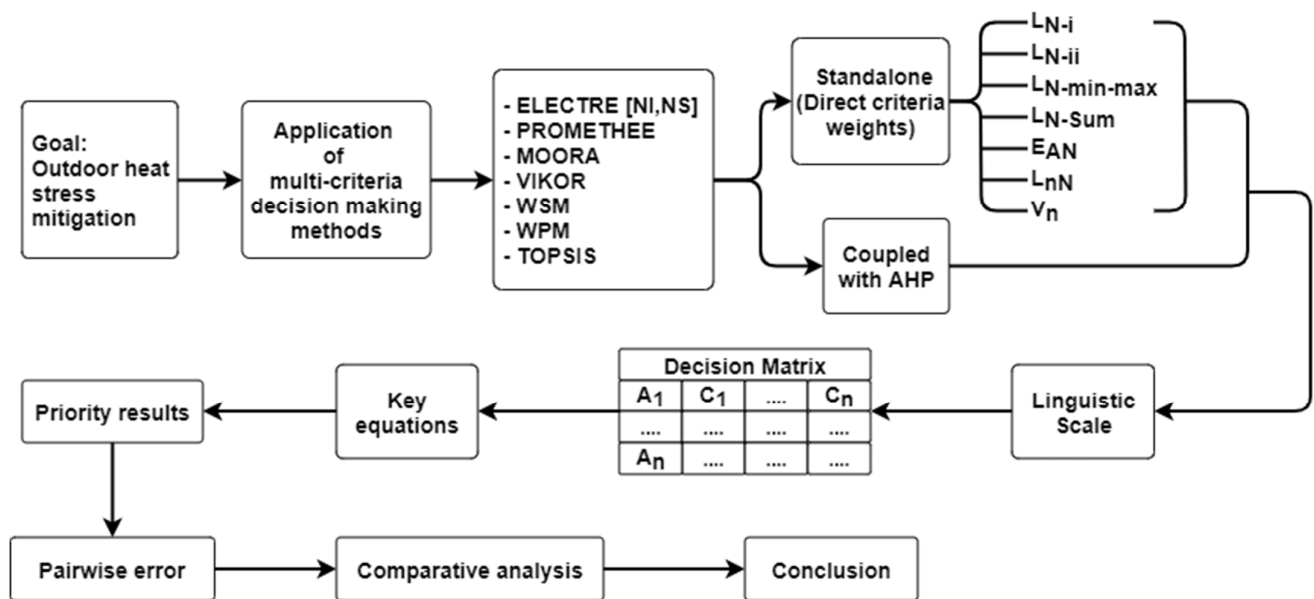


Figure 3. Research methodology.

The inputs for criteria and alternatives using the linguistic scale 1–10 was used, where high value of scale represents the high importance; for example, cost is a non-beneficial criterion, and in the case of shades the score was 8, which means it is very expensive, but the durability score was 5, which means that sometimes shades require maintenance after windstorms. All inputs were formulated in the decision matrix shown in Table 4, where criteria weights are given by direct method for the stand-alone application, and criteria weights are calculated by AHP for the combined approach by using the related formulas in Table 1.

Table 4. Decision matrix.

Direct weightage	0.45	0.15	0.20	0.20
Weightage by AHP	0.42	0.23	0.12	0.23
Interventions/Criteria	Cost	Efficiency	Durability	Environment Impacts
Water features	6	4	4	5
Surfaces	5	4	5	3
Green walls	7	6	6	7
Trees	4	7	8	8
Shades (shelter canopies)	8	4	5	2
	NB	B	B	B

## 5. Results

### 5.1. Comparative Analysis of Normalization Methods for Applied MCDM

The results show that the logarithmic normalization method had no impact on the ranking results calculated by the applied MCDMs (except for ELECTRE and VIKOR) when compared to other normalization methods. In contrast, the same ranking was observed in PROMETHEE and WSM results using all normalization techniques. Table 5 shows the consistency of similar ranking results using MCDMs under different normalization techniques.

**Table 5.** Comparative analysis of normalization methods.

Name	Results Consistency
$L_{N-i}$	ELE-NS, ELE-NI, PROMETHEE, WSM
$L_{N-ii}$	ELE-NS, ELE-NI, PROMETHEE, WSM
$L_{N-max-min}$	ELE-NS, PROMETHEE, WSM
$E_{AN}$	ELE-NS, PROM, WSM, WPM
$L_{nN}$	WSM, WPM, TOPSIS, PROMETHEE, MOORA
$V_N$	WSM, PROMETHEE, ELE-NS
$L_N-Sum$	WSM, PROMETHEE, ELE-NS, ELE-NI

### 5.2. Priority Ranking

The priority ranking for the selection of heat resilience interventions were calculated by using direct and AHP criteria weights. The ranking results obtained by stand-alone MCDM using  $L_{nN}$  and AHP-MCDM are shown in Tables 6 and 7, where alternative A1 is water feature, A2 is surfaces, A3 is green wall, A4 is trees, and A5 is shades, respectively.

**Table 6.** Rank calculated using MCDMs with  $L_{nN}$  method for normalization.

Methods	Alternatives/Interventions Priority Results				
	A1	A2	A3	A4	A5
1—ELE-NS	3	5	1	2	4
2—ELE-NI	4	5	1	3	2
3—MOORA	2	3	4	1	5
4—PROMETHEE	4	5	1	2	3
5—TOPSIS	3	2	4	1	5
6—VIKOR	2	3	5	1	4
7—WPM	4	5	1	2	3
8—WSM	4	5	1	2	3

**Table 7.** Rank calculated by AHP-MCDM.

Methods	Alternatives/Interventions Priority Results				
	A1	A2	A3	A4	A5
1—ELE-NS	4	5	1	2	3
2—ELE-NI	3	4	1	2	5
3—MOORA	3	4	2	1	5
4—PROMETHEE	3	4	2	1	5
5—TOPSIS	3	4	2	1	5
6—VIKOR	3	2	4	1	5
7—WPM	3	4	2	1	5
8—WSM	3	4	2	1	5

### 5.3. Ranking Frequency Error of Stand-Alone MCDMs and AHP-MCDMs

The obtained ranking results were showing frequency errors when comparing each applied method, which could mislead the decision. This problem was solved by evaluating the frequency of the same rankings. The pairwise frequency error was calculated by Equations (1) and (2). The sum of the standard deviation defines the frequency error and

assist to observe the variation in decision by applying different MCDMs using the same judgments. The method aims to check the consistency of the results and to evaluate the reliability of outcomes. The ends results are shown in the pairwise matrices in Table 8.

$$E_{ij} = \sqrt{\sum_{k=1}^5 (A_{kM_i} - A_{kM_j})^2} \quad (1)$$

$$E_j = \sum_{i=1}^8 E_{ij} \quad (2)$$

where:  $i$  = no of rows,  $j$  = no of columns,  $k$  = no of alternatives,  $M$  = no of methods,  $A$  = ranking result of alternative, and  $E_j$  = sum of the variation in ranking results.

**Table 8.** Pairwise comparison of frequency error matrix.

Ranking Frequency of Standalone MCDM								
	ELE-NS	ELE-NI	MOORA	PROMETHEE	TOPSIS	VIKOR	WPM	WSM
ELE-NS	0	2.45	4	1.41	4.47	4.69	1.41	1.41
ELE-NI	2.45	0	5.48	1.41	5.66	5.66	1.41	1.41
MOORA	4	5.48	0	4.69	1.41	1.41	4.69	4.69
PROMETHEE	1.41	1.41	4.69	0	4.90	5.10	0	0
TOPSIS	4.47	5.66	1.41	4.90	0	2	4.90	4.90
VIKOR	4.69	5.66	1.41	5.10	2	0	5.10	5.10
WPM	1.41	1.41	4.69	0	4.90	5.10	0	0
WSM	1.41	1.41	4.69	0	4.90	5.10	0	0
Sum	19	23.48	26.37	17.5	28.24	29.06	17.5	17.5
Ranking Frequency of AHP-MCDM								
	ELE-NS	ELE-NI	MOORA	PROMETHEE	TOPSIS	VIKOR	WPM	WSM
ELE-NS	0	2.45	2.83	2.83	2.83	4.90	2.83	2.83
ELE-NI	2.45	0	1.41	1.41	1.41	3.74	1.41	1.41
MOORA	2.83	1.41	0	0	0	2.83	0	0
PROMETHEE	2.83	1.41	0	0	0	2.83	0	0
TOPSIS	2.83	1.41	0	0	0	2.83	0	0
VIKOR	4.90	3.74	2.83	2.83	2.83	0	2.83	2.83
WPM	2.83	1.41	0	0	0	2.83	0	0
WSM	2.83	1.41	0	0	0	2.83	0	0
Sum	21.5	13.24	7.07	7.07	7.07	22.79	7.07	7.07

## 6. Discussion

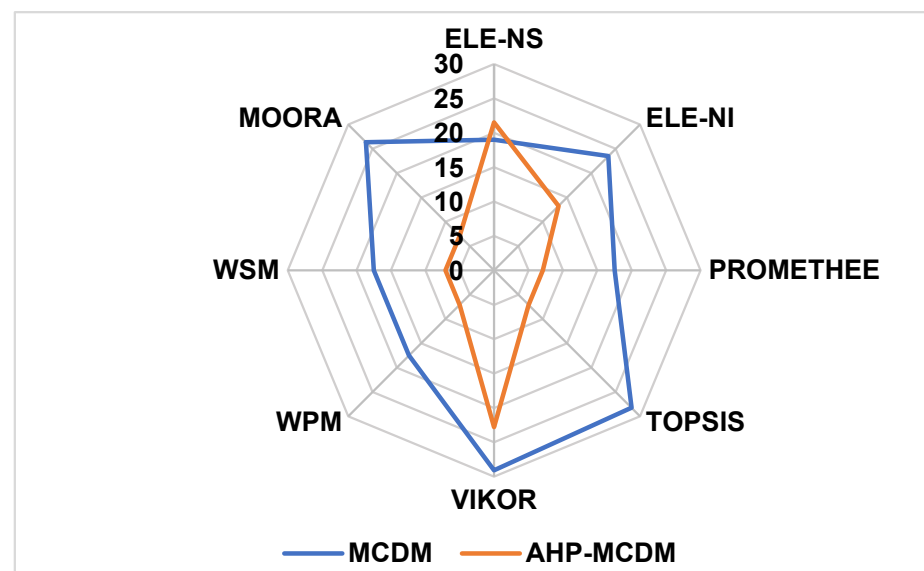
The applied MCDMs were analyzed by considering three criteria in negative and positive attributes (presented in Table 9) which are:

- *Normalization*: Positive evaluation is performed for MCDMs that gives the same results under different normalization techniques, where variations in results are taken as negative.
- *MCDM Frequency*: similar ranking results obtained by stand-alone MCDMs are assessed as positive, and high variations are considered as negative.
- *AHP-MCDM Frequency*: this criterion is used to investigate the impact of coupling AHP with applied MCDMs, where positive and negative signs show the decrease and increase in frequency variation of final ranking results, respectively.

**Table 9.** Comparative analysis of MCDM.

Methods	Assessment		
	Normalization	Frequency Error	
		MCDM	AHP-MCDM
TOPSIS	-	-	+
MOORA	-	-	+
PROMETHEE	+	+	+
WPM	-	+	+
WSM	+	+	+
VIKOR	-	-	+
ELE-NS	+	+	-
ELE-NI	-	-	+

The frequency error in the ranking results is illustrated in Figure 4, which shows that AHP helps to reduce the irregularity of the final ranking due to the pairwise subjective judgment for calculating criteria weights, which makes more reliable results in decision-making. It is compatible to combine with all the methods except ELECTRE-NS. The increased frequency error in ranking was noticed when the ELECTRE-NS model was coupled with the AHP. It was observed that WSM and PROMETHEE were not affected using any normalization techniques and gave the same ranking, which proves that they are the most reliable methods. Moreover, TOPSIS, MOORA and VIKOR models provided improved results after coupling, but the different normalization techniques could affect the final outcome.

**Figure 4.** Graph of calculated error in pairs.

Based on provided judgments (Table 4), the priority ranking obtained from the majority of the MCDMs showed that planting trees in the urban area was an effective cooling strategy that provides shade, improves air quality, and gives good cooling in certain areas where green walls improve indoor and outdoor air temperature. Additionally, the green walls enhance the aesthetics of the property. The watering method to wet the streets in the summer, planting grass on the surfaces, and water features such as fountains provides the limited cooling extent and requires extra care. While artificial shadings are expensive to install in hotspots, there was no co-benefit associated with this intervention.

## 7. Conclusions

This study was performed for the selection of intervention to mitigate outdoor UHS by applying multiple MCDMs. Eight different well known and classical techniques were computed to evaluate the priority ranking of interventions. A major concern with decision-making is that different MCDM methods provide different results for the same problem. For reliability of the outcomes, a comparative study was conducted on the basis of three criteria, which were (i) influence of normalization techniques, frequency of similar ranking results by (ii) stand-alone MCDMs, and (iii) AHP-MCDM application. It was observed that PROMETHEE and WSM were reliable methods in this field among other applied MCDMs, namely, MOORA, WPM, ELECTRE-NS, ELECTRE-NI, TOPSIS, VIKOR, which are sensitive methods and, due to variations, these MCDM models provided different priority results. Additionally, the  $L_{nN}$  was a more reasonable normalization technique, and it provided similar rankings in the majority of applied MCDMs. It was noticed that the coupling of AHP helped to minimize the frequency error through the pairwise method for criteria weights, which increased the reliability of the decision.

In this study, the priority of green walls and trees is an arbitrary output of decision makers. The ranking obtained on the parameters was not a general rule, and this procedure was carried out to check the reliability. The results were entirely based on the terrain, the perspectives, characteristics of the pilots, climatic conditions, and inputs of the decision-makers.

The improved frequency of consistent results by AHP-MCDM revealed that the ranking results mainly depended on the nature and the values of the criteria. The reasonable disagreement that was observed among the methods did not affect their reliability. As a result, MCDM models proved generally very effective for dealing with UHS problems before their implementation and selection of the best ones.

However, a possible limitation of this work is that this comparative conclusion is based only on the evaluation of ranking errors. Future works are to extend the experiment with more MCDM models and to perform sensitivity analysis to confirm that the results would not change.

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## Abbreviations

AHP	Analytic hierarchy process
EFDM	Enhanced fuzzy Delphi method
FDEMATEL	Fuzzy decision-making trial and evaluation laboratory
SMCE	Spatial Multi-Criteria Evaluation
NI	Net inferior
NS	Net superior
SWOT	Strength weakness opportunities and threat
DEA	Data envelopment analysis
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation

VIKOR	Viekriterijumsko Kompromisno Rangiranje
MOORA	Multi-Objective Optimization Ratio Analysis
MCDA	Multi Criteria Decision Analysis

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# Conclusions

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This thesis aimed to analyse the effect of Urban Heat Stress (UHS) and the applications to improve the thermal comfort. The specific work of this thesis concerns the following aspects: characterization of the relevant quantities of thermal comfort as well as action variables. Review of ambient air-cooling of cooling technologies, system dynamic modeling of thermal comfort for prediction, inventory of specific techniques, technologies and tools adapted to the problem of UHS considering different aspects in urban areas such as planning, green spaces, density, energy, air quality and occupant vulnerability. Field monitoring with sensors to measure relevant variables and take action to minimize the effects of heat stress. Development of a decision support tool allowing flexible, dynamic, and predictive use for both designers and users. The main objectives of this research are formulated as follows:

- ❖ To investigate prior research and evaluate the ambient air cooling by green, blue and grey interventions;
- ❖ To investigate prior research on decision support tools for urban heat resilience;
- ❖ Survey on different outdoor heat stress indices;
- ❖ To develop an optimized predictive model for thermal comfort assessment using artificial intelligence;
- ❖ To evaluate the effect of social and environmental risk factors and calculate the heat vulnerability index of a medium sized city, Amiens (case study);
- ❖ Field monitoring by using thermal camera and Kestrel 5400 to evaluate the cooling effect of existing measures mainly in public spaces;
- ❖ Implementation and comparative study of multi-criteria decision methods for the selection of urban heat mitigation intervention;

In the following, we address some concluding remarks for each chapter.



In Chapter 1, previously published studies on the cooling effect of vegetation, water features and shading devices were investigated. Data on the ambient air-cooling effect was extracted from each study based on the considered urban settings/locations (for generic/real urban areas). In addition, another review study of theoretical research and published tools on decision support for urban heat resilience was carried out with their mathematical models and target parameters. Existing decision support tools are analysed with benchmarking criteria that should be covered by the decision support system for UHS mitigation. It is concluded;

- ❖ Water features, green walls and artificial shading provide a comparable air-cooling effect during the daytime in summer. Green walls and shades are expensive to intervene.
- ❖ Cooling effect of reviewed interventions depends on the local climate and geography.
- ❖ It was noted that online assessment DSTs are practical but spatial coverage remains the limit.
- ❖ Many existing decision tools for UHS are published but there is still a gap that can be improved by considering all the considered criteria.

In Chapter 2, the survey map was produced for OHSIs used by environmental agencies around the world. The aim of this study was to quantify the variation coefficient of evolving parameters of HI, CET, PMV, SSI, DI, UTCI, WBGT. Sensitivity analysis was performed by simulating the indices using the min-max function. The obtained results confirm;

- ❖ The selection of the index to estimate the UHS depends on the regional weather conditions or the age group and activities of the inhabitants.
- ❖ WBGT, HSI, and CET are recommended indices which can be measured using sensors to avoid errors.
- ❖ HI, UTCI and WBGT indicate a slightly warm comfort zone while PMV, SSI, CET, DI indicate a comfortable zone using the same input.
- ❖ HI is a very influential index with fewer variations can lead to increased thermal discomfort.

- ❖ CET underestimates the thermal comfort zone.

In line with the 4<sup>th</sup> research objective, in Chapter 3, emphasis was placed on heat stress modeling for prediction. A system dynamic approach was used, which allows the identification of significant meteorological variables influencing heat stress. The obtained results confirm;

- ❖ SVM was a suitable machine learning technique that estimated heat stress with 98% accuracy, while GRU was the finest deep learning model for optimized prediction of PET, PMV and  $T_{mrt}$  with 99% precision %.
- ❖ The developed model is useful only for the summer season (April-September).
- ❖ The developed simulation tool can help users to analyse and choose the appropriate heat stress index between PMV and PET by comparing their current feeling.
- ❖ The tool will allow the developer to analyse user inputs for further analysis.

Chapter 4 presented a case study of a medium-sized city that aimed to derive heat vulnerability index mapping using PCA. The index was derived for the hottest days in the last 3 years. The output maps identified hot spots through comprehensive GIS analysis. The following conclusions can be drawn:

- ❖ A high correlation coefficient was observed between poor air quality and 2019-2020 heat events, especially with  $O_3$ .
- ❖ High HVI observed in three typical areas: (1) areas with dense population and low vegetation, (2) areas with artificial surfaces (built-up areas), and (3) industrial areas. Low HVI areas are found in natural landscapes such as rivers and grasslands.
- ❖ Research has proven that poor air quality and heat events are interrelated and that the combined effect of two events could increase risk and vulnerability.
- ❖ The current approach may be applicable to other regions of the world, including large cities, to assess heat-related vulnerabilities and help authorities to take mitigation measures.

- ❖ The challenges of this study are; irregular and limited weather and air quality monitoring stations.
- ❖ The disadvantage of this study is that district heating and cooling facilities were not considered due to lack of data.

The field measurements are carried out last summer (2021) at 3 public spaces in city centre. It was estimated;

- ❖ *Tilia cordata* mill *malvacae* gives a significant cooling effect by lowering the average  $T_a$  by 3.7°C whereas Golden rain tree drops by 0.6°C and the cooling extent wider than other sites due to presence of water fountain.
- ❖ Cooling effect depends on the characteristics and span of the site.

The last research objective is presented chapter 5, which focused on the decision-making for prioritizing the heat stress mitigation interventions with help of MCDMs. In first step, AHP was implemented for the selection of intervention to develop the criteria framework and confirm the reliability of the method. Secondly, ELECTRE (NI, NS) TOPSIS, PROMETHEE, VIKOR, MOORA, WSM and WPM are applied for the selection of heat resilience measure under certain criteria. The models are applied in two ways: AHP-integrated and non-integrated for better precision. It is concluded;

- ❖ LnN is an efficient normalization technique that does not greatly influence the final ranking.
- ❖ WSM and PROMETHEE provide reliable and consistent output. These techniques do not vary between different normalization techniques.
- ❖ The integration of AHP has improved the quality of the results except with ELECTRE-NS which increases the inconsistency in the final classification.
- ❖ After a comparative analysis of the priority ranking calculated from all the methods, it is concluded that green walls and trees are the top priority.
- ❖ Incomplete and inconsistent judgments was the real challenge as missing information could lead to a wrong choice.

# List of Publications

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## *Journal papers*

1. Qureshi, A.M.; Rachid, A.; Bartlett, D. Quantifying the cooling effect of urban heat stress interventions: A review. *International Journal of Global Warming*. (accepted) (2022).
2. Qureshi, A.M.; Rachid, A. Review and Comparative Study of Decision Support Tools for the Mitigation of Urban Heat Stress, *Climate* 2021, 9, 102. <https://doi.org/10.3390/cli9060102>.
3. Qureshi, A. M., & Rachid, A. (2022). Heat stress modeling using neural networks technique. *IFAC-Papers Online*, 55(12), 13-18. <https://doi.org/10.1016/j.ifacol.2022.07.281>
4. Qureshi, A.M.; Rachid, A. Heat Vulnerability Index Mapping: A Case Study of a Medium-Sized City (Amiens). *Climate* 2022, 10, 113. <https://doi.org/10.3390/cli10080113>
5. Qureshi AM, Rachid A. Comparative Analysis of Multi-Criteria Decision-Making Techniques for Outdoor Heat Stress Mitigation. *Applied Sciences*. 2022; 12(23):12308. <https://doi.org/10.3390/app122312308>

## *Conference Paper*

1. A. M. Qureshi and A. Rachid, "An Analytic Hierarchy Process for urban heat stress mitigation," 2022 2nd International Conference on Digital Futures and Transformative Technologies (ICoDT2), 2022, pp. 1-6, <https://doi: 10.1109/ICoDT255437.2022.9787481>

## *List of papers in preparation*

1. Sensitivity analysis of heat stress indices. (Submitted)

## Résumé

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Le stress thermique est une sensation inconfortable, lorsque le corps est incapable de maintenir une température saine en réponse aux conditions environnementales chaudes pendant les activités quotidiennes telles que dormir, voyager, travailler. L'intensité croissante du stress thermique dans les zones urbaines est devenue une préoccupation importante en raison de son effet direct et néfaste sur la santé humaine et les activités économiques.

Il a été observé au cours des dernières décennies que l'augmentation rapide de l'intensité des vagues de chaleur en milieu urbain a suivi le réchauffement climatique. Ces vagues de chaleur extrêmes ont un impact dangereux sur l'environnement urbain et la population, augmentant à terme le taux de morbidité et de mortalité.

La densité de population est le facteur majeur car la vulnérabilité aux vagues de chaleur augmente et donne lieu au phénomène d'îlot de chaleur urbain (UHI) - où la ville est plus chaude que ses environs. La densité des zones urbaines augmente rapidement en raison de l'augmentation des taux de natalité et la migration des personnes des milieux ruraux pour améliorer leur vie au moyen de meilleurs revenus, de ressources, d'une meilleure société et, finalement, d'une vie meilleure.

Les activités anthropiques humaines quotidiennes dans les communautés urbaines émanent un nombre énorme de particules de contamination dans l'air urbain, ce qui augmente la vulnérabilité des personnes aux toxines de l'air. De plus, la superposition du stress thermique et de la contamination de l'air rend les gens progressivement impuissants face à l'impact de chaque risque approprié.

De nombreuses villes ont appliqué des plans d'intervention d'urgence liés à la chaleur pour réduire les taux de mortalité pendant la canicule. La combinaison de fortes vagues de chaleur et d'une mauvaise qualité de l'air entraîne des risques pour la santé. Le stress thermique peut entraîner un épuisement dû à la chaleur, des crampes de chaleur et des éruptions cutanées et, en raison d'une exposition à long terme, il provoque un coup de chaleur. Les enfants, les personnes âgées, les personnes vivant seules, les femmes enceintes, les asthmatiques et les patients cardio sont particulièrement vulnérables aux deux événements extrêmes (chaleur et pollution) qui nécessitent des interventions supplémentaires.

Dans la situation actuelle, si rien n'est adapté pour atténuer l'intensité du stress thermique dans les zones urbaines, l'extrémité de température se propagerait fortement sur la sphère terrestre d'ici 2100. L'élévation incontrôlée de la chaleur extrême aurait un impact considérable sur les communautés et les écosystèmes, ce qui rendrait finalement plus difficile d'y faire face.

Des stratégies d'atténuation du stress thermique doivent être appliquées dans les zones urbaines, afin de préserver l'environnement et la santé humaine. Intervenir sur les mesures de résistance à la chaleur, développer un système d'aide à la décision est un défi. Cette thèse porte sur le confort thermique qui combine la modélisation de la prédiction du stress thermique, la cartographie de la vulnérabilité à la chaleur, les mesures sur le terrain et l'application de méthodes de décision multicritères. Cette thèse est composée de 5 chapitres. Les chapitres 1 à 5 sont basés sur des articles de revues ; les conclusions sont fournies à la fin. Le résumé de chaque chapitre est donné ci-dessous.

**Chapitre 1 :** Les interventions contribuent non seulement à la santé physiologique des citoyens, mais ont également un impact psychologique. Lorsque les conditions environnementales sont extrêmes avec un rayonnement solaire intense et que les niveaux de chaleur augmentent, il faut envisager des actions préventives et des ressources pour mettre en œuvre des interventions de refroidissement en milieu urbain. Lors de la sélection de la stratégie de résistance à la chaleur la plus appropriée, des critères importants doivent être pris en compte, tels que l'effet de refroidissement, le coût, la maintenance et l'acceptation du public.

Au total, 71 articles de revues sont examinés, publiés en anglais et axés sur les interventions qui améliorent le confort thermique. Les données sur l'effet de refroidissement sont extraites de ces articles de journaux pour étudier l'efficacité des stratégies d'atténuation du stress thermique. Sur la base de l'analyse des données extraites, les réalisations passées sur ce sujet de recherche sont documentées et le refroidissement moyen de l'installation des interventions vert bleu et gris est estimé.

Les objectifs de cet examen sont (i) de fournir un aperçu des stratégies d'atténuation UHS, (ii) de quantifier l'effet de refroidissement des caractéristiques naturelles et construites sur la base de différents indicateurs, principalement température de l'air (iii) d'analyser les résultats pour déterminer la plus efficace méthode pour réduire le SSU (iv) identifier les Co-bénéfices associés à ces interventions.

Tous les types de mesures d'atténuation qui sont examinés dans cette étude fournissent un refroidissement, mais l'effet dépend du climat et de la géographie locaux. Les recherches futures devraient se concentrer sur le développement d'un outil pratique d'aide à la décision qui peut aider les décideurs à sélectionner une mesure d'adaptation en fonction des caractéristiques du site proposé, des circonstances sociales et économiques locales et des contraintes.

De plus, un examen est effectué sur la base des outils d'aide à la décision (DST) existants qui ont été développés pour atténuer les effets du stress thermique urbain (UHS) en utilisant des solutions basées sur la nature. Il contribue à la problématique UHS en : (i) identifiant les facteurs clés les plus importants d'un DST utilisé pour l'atténuation de la chaleur urbaine, (ii) présentant des méthodes multicritères appliquées à la résilience thermique urbaine, (iii) passant en revue les données spatiales et non spatiales existantes. DST, (iv) et analyse, classification et classement des DST. L'observation pourrait aider les décideurs à travers un aperçu des avantages et des inconvénients des DST existants et indiquer quel outil fournit un soutien maximal pour choisir et planifier des mesures de résilience thermique de la phase de conception à la phase d'atténuation de la chaleur. Les résultats obtenus montrent que l'analyse décisionnelle multicritère (MCDA) peut être utilisée pour n'importe quel site pilote et que les critères peuvent être adaptés à l'emplacement donné en conséquence. Il a été constaté que les outils spatiaux basés sur le SIG disposent d'un système d'aide à la décision (DSS) efficace car ils offrent une évaluation rapide des interventions et prédisent les effets à long terme de la chaleur urbaine. Les outils ont été comparés selon 15 critères qui doivent être couverts par la DST pour éliminer le risque de chaleur urbaine. Il est conclu qu'en dépit de nombreuses publications existantes et d'outils rapportés, il y a encore place à l'amélioration, ce qui peut être réalisé par une approche holistique traitant des aspects subjectifs et objectifs du stress thermique, combinant diverses entrées de capteurs ainsi que d'experts et d'habitants. Retour d'expérience, et en utilisant différentes techniques telles que MCDA, GIS, planification urbaine et, à terme, des outils d'intelligence artificielle pour corréler ces aspects entre eux afin de développer un DSS fiable pour l'atténuation du stress thermique.



**Chapitre 2 :** Ce chapitre est un état de l'art qui comprend le contexte du stress thermique et les modèles existants sont discutés dans ces sections. Une enquête sur les indices de stress thermique extérieur est menée pour présenter leurs modèles mathématiques existants et mettre en évidence les différents indices de chaleur utilisés officiellement pour mesurer le confort thermique dans différentes régions du monde. Après l'étude des indices de chaleur, on remarque que la plupart des indices peuvent être mesurés et calibrés directement en utilisant des équations et certains indices secondaires peuvent être estimés par différentes méthodes complexes évaluées par leurs modèles. L'analyse de sensibilité des indices de stress thermique les plus courants qui peuvent être estimés par des modèles mathématiques directs, c'est-à-dire la température effective corrigée (CET), l'indice de chaleur (HI), l'indice de mijotage d'été (SSI), le vote moyen prévu (PMV), l'indice d'inconfort (DI), Wet Bulb Globe Temperature (WBGT), Universal Thermal Climate Index (UTCI) sont programmés et simulés pour analyser le coefficient de variation de leurs paramètres évolutifs. Ces indices opérationnels sont également simulés pour analyser la sensibilité des zones d'inconfort à certaines variations d'été sous la fonction minmax.

Cette étude conclut après l'enquête que chaque région du globe choisit des indices de chaleur en fonction de certains paramètres spécifiques. Les facteurs qui ont influencé la sélection sont : la sensibilisation des personnes particulièrement vulnérables, les entretiens physiques (connaître l'âge, le sexe, les sensations, les styles vestimentaires, les activités), la corrélation entre les systèmes immunitaires et le nombre d'événements de santé cardiaque. De nombreux pays ne se soucient pas beaucoup des indices de stress thermique, sont moins axés sur la résolution des aléas climatiques et disposent de moins de ressources pour prêter attention aux problèmes environnementaux.

Les résultats montrent que la température de l'air est le paramètre le plus sensible en particulier pour l'estimation de HI, SSI, DI et UTCI alors que l'humidité relative est négligeable sauf dans le cas de SSI et HI. De plus, il est recommandé que les indices mesurables tels que WBGT, HI et CET puissent éviter les erreurs qui dépendent des hypothèses qui peuvent survenir lors de l'estimation du stress thermique à l'aide de modèles instables qui sont difficiles à réaliser dans la pratique.

**Chapitre 3 :** La température physiologique équivalente (PET) et le vote moyen prévu (PMV) sont des indices de chaleur complexes qui peuvent être calculés par les modèles de bilan énergétique de Munich pour les modèles individuels et Fangers respectivement. Le PET est principalement utilisé pour quantifier le stress thermique extérieur et où le PMV est principalement utilisé pour l'évaluation du confort thermique intérieur. L'intelligence dynamique et artificielle du système est utilisée pour la modélisation prédictive de la TEP, de la température radiante moyenne et de la PMV. Les cinq paramètres météorologiques les plus importants tels que la température de l'air, le rayonnement global, l'humidité relative, la température de surface et la vitesse du vent sont pris en compte pour l'évaluation du stress thermique. Trois approches d'apprentissage automatique qui sont : la machine à vecteurs de support, l'arbre de décision et la forêt aléatoire sont utilisées pour prédire le stress thermique plus tard, des approches d'apprentissage en profondeur, c'est-à-dire la mémoire longue à court terme, l'unité récurrente fermée (GRU) et les réseaux de neurones récurrents simples sont utilisées, et la performance des approches développées est évaluée

L'analyse comparative des résultats obtenus a montré que SVM est une approche efficace, mais GRU est la plus fiable et la plus précise avec une efficacité de test élevée parmi d'autres algorithmes utilisés pour traiter les données météorologiques et estimer le niveau de confort thermique. Le modèle a été testé en deux phases pour les sorties ( $T_{mrt}$ , PMV, PET) une fois avec les données de test et

une fois avec les données réelles de l'été 2021 pour valider le modèle avec le logiciel de référence. Un outil de simulation basé sur le Web est développé pour les utilisateurs pour l'évaluation du stress thermique qui permet aux utilisateurs de sélectionner la gamme d'échelles de confort thermique en fonction de leur perception qui dépend du facteur d'âge, de l'adaptabilité aux conditions météorologiques locales et de l'habitude de tolérer les événements de chaleur. Il donne également un avertissement à l'utilisateur par code couleur sur le niveau d'inconfort qui l'aide à planifier et à gérer ses activités de plein air.

**Chapitre 4** : Après l'évaluation du stress thermique, il est également nécessaire d'analyser les points chauds et les zones vulnérables. Nous avons évalué l'indice de vulnérabilité à la chaleur (HVI) à Amiens pour les journées de chaleur extrême enregistrées pendant trois ans (2018-2020). Nous avons utilisé la technique d'analyse en composantes principales (PCA) pour la cartographie de vulnérabilité à échelle fine. Les principaux types de données examinées comprenaient (a) des données socio-économiques et démographiques, (b) la pollution de l'air, (c) l'utilisation et l'occupation des terres, (d) les maladies liées à la chaleur des personnes âgées, (e) la vulnérabilité sociale et (f) les données de télédétection (température de la surface terrestre (LST), altitude moyenne, indice de végétation par différence normalisée (NDVI) et indice de différence normalisée de l'eau (NDWI)). Les cartes de sortie ont identifié les zones chaudes grâce à une analyse GIS complète. Les cartes résultantes ont montré qu'un HVI élevé existe dans trois zones typiques : (1) les zones à population dense et à végétation basse, (2) les zones avec des surfaces artificielles (zones bâties) et (3) les zones industrielles. Les zones à faible HVI se trouvent dans des paysages naturels tels que des rivières et des prairies. Cette approche peut être utile aux décideurs pour cibler les zones chaudes afin de planifier des mesures de résistance à la chaleur.

Après cette étude, des techniques de fusion de données sont recommandées pour une meilleure précision de l'analyse et du développement du HVI, augmentant ainsi la fiabilité et diminuant la redondance pour soutenir le processus de prise de décision. Cette recherche met en lumière les solutions suivantes qui peuvent aider les citoyens à lutter contre les épisodes de chaleur :

- ❖ Fournir des informations aux populations locales sur les avertissements de chaleur et les précautions, en accordant une plus grande attention aux personnes vulnérables ;
- ❖ Mise en œuvre de pratiques adaptatives proactives telles que les ombrages, les infrastructures bleues et la verdure lorsque le score HVI est supérieur à 6 ;
- ❖ Surveillance régulière pendant la saison estivale dans la ville.

De plus, un plan de mesure a été préparé après avoir sélectionné trois sites pilotes à pied dans le centre-ville d'Amiens, en France. Ces sites sont des espaces publics ouverts où les piétons et les touristes visitent et utilisent souvent les bancs publics. Aux heures de pointe d'une journée chaude, l'ombre des arbres et les mesures environnantes telles que les fontaines d'eau, la végétation contribuent à rendre l'atmosphère agréable en réduisant la température de l'air. Des mesures ont été effectuées au cours des derniers étés (2021) à Amiens à l'aide d'un capteur nommé Kestrel 5400 pour surveiller l'impact de refroidissement des espèces d'arbres existantes sur les sites pilotes choisis. De plus, deux cycles de surveillance de 15 minutes ont été effectués pour toutes les espèces chaque jour et chaque échantillon a été enregistré toutes les 10 secondes. Les jours de mesure étaient ceux où le ciel était clair entre les heures de pointe (12h00 à 16h00) et la position du soleil était du sud-est au sud-ouest. Les images thermiques sont capturées avant les mesures avec la caméra thermique FLIR E6. L'analyse de la surveillance enregistrée

a montré que l'effet de refroidissement des interventions dépend des caractéristiques du pilote et de la taille de la zone.

**Chapitre 5** : La sélection de l'intervention pour les emplacements souhaitables est importante pour les décideurs qui tiennent compte de certains critères. Les MCDM (Multi-Criteria Decision Methods) sont des aides pour sélectionner et hiérarchiser les alternatives étape par étape. Dans ce chapitre, les MCDM sont appliqués, ce qui aide à sélectionner et hiérarchiser les mesures d'atténuation étape par étape. Tout d'abord, une approche basée sur le processus de hiérarchie analytique (AHP) est appliquée pour choisir les mesures appropriées pour les points chauds. L'évaluation des mesures est obtenue à partir d'un questionnaire où le jugement humain est utilisé pour une comparaison, en fonction de leur perception et de leurs priorités. Ces techniques peuvent aider dans de nombreux domaines d'ingénierie où le problème est complexe et avancé. Cependant, il existe certaines limites des différents MCDM qui réduisent la fiabilité de la décision qui doit être améliorée et mise en évidence. Dans cette étude Elimination and Choice Expressing Reality (ELECTRE) NI (Net Inferior), NS (Net Superior), Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Vlekkriterijumsko KOMPromisno Rangiranje (VIKOR), l'analyse du ratio d'optimisation multi-objectifs (MOORA), la méthode de la somme des poids (WSM) et la méthode du produit pondéré (WPM) sont appliquées pour la sélection des mesures d'atténuation de la chaleur urbaine selon certains critères

Les modèles sont appliqués à l'aide de critères de pondération déterminés de deux manières ; (i) méthode de pondération directe et (ii) processus de hiérarchie analytique (AHP) pour un facteur de pondération précis grâce à une comparaison par paires. Cette recherche numérique a évalué la fiabilité des MCDM utilisant la même matrice de décision sous différentes techniques de normalisation et montre

l'impact de l'AHP sur la décision. Les résultats montrent que WSM et PROMETHEE fournissent des résultats fiables et cohérents pour toutes les techniques de normalisation.

De plus, le LnN est une technique de normalisation plus raisonnable et fournit un classement similaire dans la majorité des MCDM appliqués. On remarque que le couplage d'AHP aide à minimiser l'erreur de fréquence par la méthode par paires pour les poids des critères qui augmentent la fiabilité de la décision. Dans cette étude, la priorité des murs verts et des arbres est une sortie arbitraire des décideurs. Le classement obtenu sur les paramètres n'est pas une règle générale et cette procédure a été effectuée pour vérifier la fiabilité. Les résultats sont entièrement basés sur le terrain, les perspectives, les caractéristiques des pilotes, les conditions climatiques et les apports des décideurs.

L'amélioration de la fréquence des résultats de classement similaires par AHP-MCDM a révélé que les résultats de classement dépendent principalement de la nature et des valeurs des critères. Le désaccord raisonnable qui a été observé entre les méthodes n'a pas affecté leur fiabilité. En conséquence, les modèles MCDM se sont avérés généralement très efficaces pour traiter le problème UHS avant leur mise en œuvre et sélectionner les meilleurs.